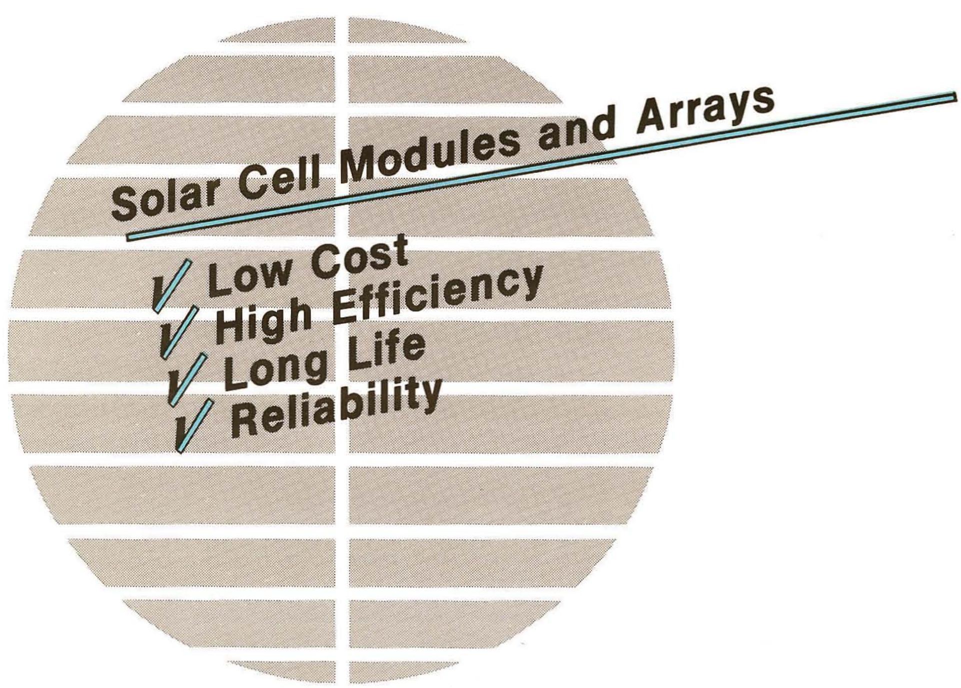
JPL Publication 86-31

Electricity from Photovoltaic Solar Cells

Flat-Plate Solar Array Project Final Report

Volume VI: Engineering Sciences and Reliability

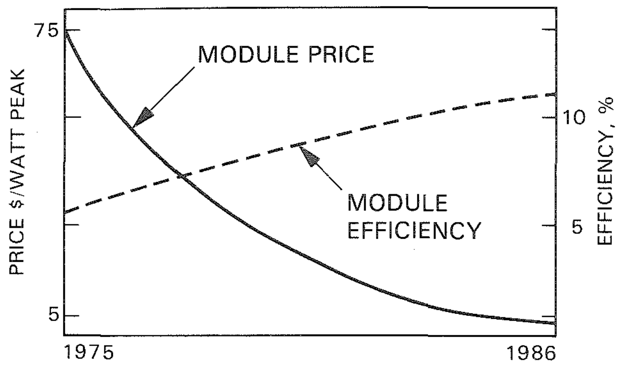
11 Years of Progress



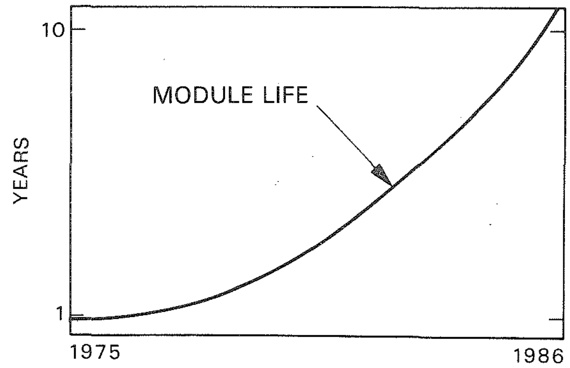
October 1986

Project Managed by the Jet Propulsion Laboratory for the U.S. Department of Energy

Photovoltaic Module Progress

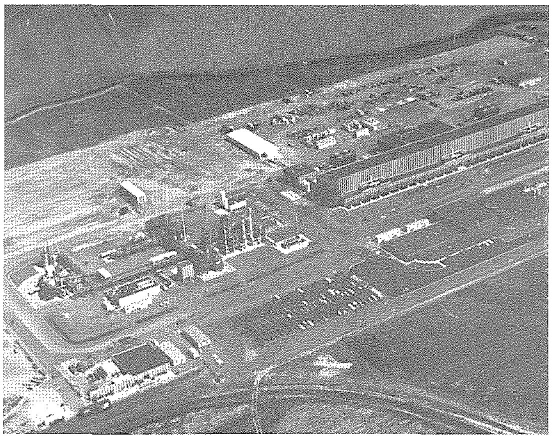


Flat or non-concentrating module prices have dropped as module efficiencies have increased. Prices are in 1985 dollars for large quantities of commercial products.

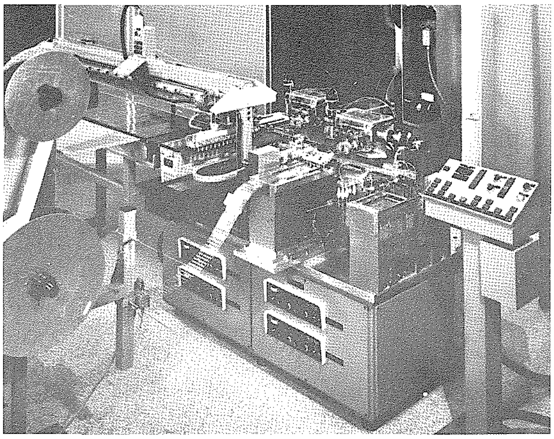


Typical module lifetimes were less than 1 year but are now estimated to be greater than 10 years. (Ten-year warranties are now available.)

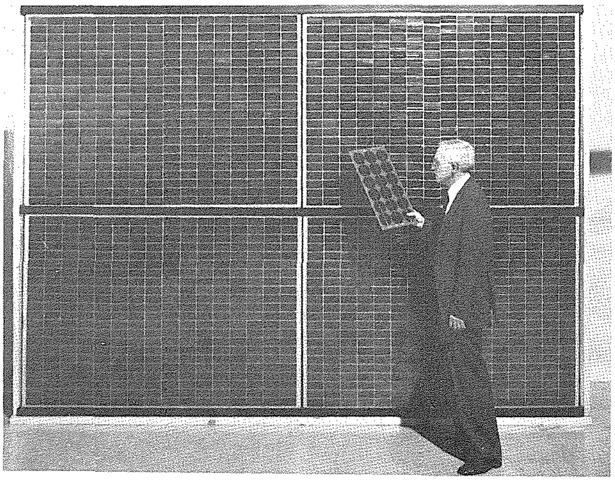
Technology advancement in crystalline silicon solar cells and modules (non-concentrating).



Union Carbide Corporation (UCC) funded the now operational silicon refinement production plant with 1200 MT/year capacity. DOE/FSA-sponsored efforts were prominent in the UCC process research and development.



The automated machine interconnects solar cells and places them for module assembly. The second-generation machine made by Kulicke and Soffa was cost shared by Westinghouse Corporation and DOE/FSA.



A Block I module (fabricated in 1975), held in front of four Block V modules, represents the progress of an 11-year effort. The modules, designed and manufactured by industry to FSA specifications and evaluated by FSA, rapidly evolved during the series of module purchases by DOE/FSA.

More technology advancements of the cooperative industry/university/ DOE/FSA efforts are shown on the inside back cover. Use of modules in photovoltaic power systems are shown on the outside back cover.

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Electricity from Photovoltaic Solar Cells

Flat-Plate Solar Array Project Final Report

Volume VI: Engineering Sciences and Reliability

R.G. Ross, Jr.
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11 Years of Progress

October 1986

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Final Report Organization

This FSA Final Report (JPL Publication 86-31, 5101-289, DOE/JPL 1012-125, October 1986) is composed of eight volumes, consisting of an Executive Summary and seven technology reports:

Volume I: Executive Summary.

Volume II: Silicon Material.

Volume III: Silicon Sheet: Wafers and Ribbons

Volume IV: High-Efficiency Solar Cells.

Volume V: Process Development.

Volume VI: Engineering Sciences and Reliability.

Volume VII: Module Encapsulation.

Volume VIII: Project Analysis and Integration.

Two supplemental reports included in the final report package are:

FSA Project: 10 Years of Progress, JPL Document 400-279, 5101-279, October 1985.

Summary of FSA Project Documentation: Abstracts of Published Documents, 1975 to 1986, JPL Publication 82-79 (Revision 1), 5101-221, DOE/JPL-1012-76, September 1986.

Upon request, this FSA Final Report (JPL Publication 86-31) and the two supplemental reports (JPL Document 400-279 and JPL Publication 82-79) are individually available in print from:

National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

Abstract

The Flat-Plate Solar Array (FSA) Project, funded by the U.S. Government and managed by the Jet Propulsion Laboratory, was formed in 1975 to develop the module/array technology needed to attain widespread terrestrial use of photovoltaics by 1985. To accomplish this, the FSA Project established and managed an Industry, University, and Federal Government Team to perform the needed research and development.

This volume of the series of final reports documenting the FSA Project deals with the Project's activities directed at developing the engineering technology base required to achieve modules that meet the functional, safety and reliability requirements of large-scale terrestrial photovoltaic systems applications. These activities included: (1) development of functional, safety, and reliability requirements for such applications; (2) development of the engineering analytical approaches, test techniques, and design solutions required to meet the requirements; (3) synthesis and procurement of candidate designs for test and evaluation; and (4) performance of extensive testing, evaluation, and failure analysis to define design shortfalls and, thus, areas requiring additional research and development.

During the life of the FSA Project, these activities were known by and included a variety of evolving organizational titles: Design and Test, Large-Scale Procurements, Engineering, Engineering Sciences, Operations, Module Performance and Failure Analysis, and at the end of the Project, Reliability and Engineering Sciences.

This volume provides both a summary of the approach and technical outcome of these activities and provides a complete Bibliography (Appendix A) of the published documentation covering the detailed accomplishments and technologies developed.

Foreword

Throughout U.S. history, the Nation's main source of energy has changed from wood to coal to petroleum. It is inevitable that changes will continue as fossil fuels are depleted. Within a lifetime, it is expected that most U.S. energy will come from a variety of sources, including renewable energy sources, instead of from a single type of fuel. More than 30% of the energy consumed in the United States is used for the generation of electricity. The consumption of electricity is increasing at a faster rate than the use of other energy forms and this trend is expected to continue.

Photovoltaics, a promising way to generate electricity, is expected to provide significant amounts of power in years to come. It uses solar cells to generate electricity directly from sunlight, cleanly and reliably, without moving parts. Photovoltaic (PV) power systems are simple, flexible, modular, and adaptable to many different applications in an almost infinite number of sizes and in diverse environments. Although photovoltaics is a proven technology that is cost-effective for hundreds of small applications, it is not yet cost-effective for large-scale utility use in the United States. For widespread economical use, the cost of generating power with photovoltaics must continue to be decreased by reducing the initial PV system cost, by increasing efficiency (reduction of land requirements), and by increasing the operational lifetime of the PV systems.

In the early 1970s, the pressures of the increasing demand for electrical power, combined with the uncertainty of fuel sources and ever-increasing prices for petroleum, led the U.S. Government to initiate a terrestrial PV research and development (R&D) project. The objective was to reduce the cost of manufacturing solar cells and modules. This effort, assigned to the Jet Propulsion Laboratory, evolved from more than a decade-and-a-half of spacecraft PV power-system experience and from recommendations of a conference on Solar Photovoltaic Energy held in 1973 at Cherry Hill, New Jersey.

This Project, originally called the Low-Cost Solar Array Project, but later known as the Flat-Plate Solar Array (FSA) Project, was based upon crystalline-silicon technology as developed for the space program. During the 1960s and 1970s, it had been demonstrated that photovoltaics was a dependable electrical power source for spacecraft. In this time interval, solar-cell quality and performance improved while the costs decreased. However, in 1975 the costs were still much too high for widespread use on Earth. It was necessary to reduce the manufacturing costs of solar cells by a factor of approximately 100 if they were to be a practical, widely used terrestrial power source.

The FSA Project was initiated to meet specific cost, efficiency, production capacity, and lifetime goals by R&D in all phases of flat-plate module (non-concentrating) technology, from solar-cell silicon material purification through verification of module reliability and performance.

The FSA Project was phased out at the end of September 1986.

Acknowledgments

During the life of the Flat-Plate Solar Array Project, many Jet Propulsion Laboratory personnel played important roles in the Engineering Sciences and Reliability activities. Key contributors included:

Area Management

L. Dumas (1976 to 1981)
R. Ross (1975 to 1986)
D. Runkle (1981 to 1984)
M. Smokler (1984 to 1986)

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G. Downing	Q. Kim	A. Shumka
J. Fortenberry	R. Lee	M. Smokler
R. Greenwood	E. Miller	S. Sollock

In addition to the above engineers, the contributions of the many technicians, administrative assistants, and secretaries who supported these activities through the years are gratefully acknowledged. Special appreciation is expressed to W. Caldwell, J. Gomez, E. Jetter, A. Johnson, J. Kiehl, S. Leeland, D. Robinson, K. Stern, and O. Witte.

The area-management personnel listed above were also line-management group supervisors. As with most personnel, they served both the Project management and their line section managers. Both sources greatly facilitated the accomplishments described herein. The unwavering support of Project Managers Bob Forney and Bill Callaghan, and Section Managers Joe Spiegel and Larry Dumas are much appreciated.

We also recognize R. Sugimura and L. Wen, who assembled the lengthy Bibliography appended to this document, and J. Kiehl who typed the manuscript.

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FSA Project Summary

The Flat-Plate Solar Array (FSA) Project, a Government-sponsored photovoltaic (PV) project, was initiated in January 1975 with the intent to stimulate the development of PV systems for economically competitive, large-scale terrestrial use. The Project's goal was to develop, by 1985, the technology needed to produce PV modules with 10% energy conversion efficiency, a 20-year lifetime, and a selling price of $0.50/W$_p$ (in 1975 dollars). The key achievement needed was cost reduction in the manufacture of solar cells and modules.

As manager, the Jet Propulsion Laboratory organized the Project to meet the stated goals through research and development (R&D) in all phases of flat-plate module technology, ranging from silicon-material refinement through verification of module reliability and performance. The Project sponsored parallel technology efforts with periodic progress reviews. Module manufacturing cost analyses were developed that permitted cost-goal allocations to be made for each technology. Economic analyses, performed periodically, permitted assessment of each technical option's potential for meeting the Project goal and of the Project's progress toward the National goal. Only the most promising options were continued. Most funds were used to sponsor R&D in private organizations and universities, and led to an effective Federal Government-University-Industry Team that cooperated to achieve rapid advancement in PV technology.

Excellent technical progress led to a growing participation by the private sector. By 1981, effective energy conservation, a leveling of energy prices, and decreased Government emphasis had altered the economic perspective for photovoltaics. The U.S. Department of Energy's (DOE's) National Photovoltaics Program was redirected to longer-range research efforts that the private sector avoided because of higher risk and longer payoff time. Thus, FSA concentrated its efforts on overcoming specific critical technological barriers to high efficiency, long life, reliability, and low-cost manufacturing.

To be competitive for use in utility central-station generation plants in the 1990s, it is estimated that the price of PV-generated power will need to be $0.17/kWh (1985 dollars). This price is the basis for a DOE Five-Year Photovoltaics Research Plan involving both increased cell efficiency and module lifetime. Area-related costs for PV utility plants are significant enough that flat-plate module efficiencies must be raised to between 13 and 17%, and module life extended to 30 years. Crystalline silicon, research solar cells (non-concentrating) have been fabricated with more than 20% efficiency. A full-size experimental 15% efficient module also has been fabricated. It is calculated that a multimegawatt PV power plant using large-volume production modules that incorporate the latest crystalline silicon technology could produce power for about $0.27/kWh (1985 dollars). It is believed that $0.17/kWh (1985 dollars) is achievable, but only with a renewed and dedicated effort.

Government-sponsored efforts, plus private investments, have resulted in a small, but growing terrestrial PV industry with economically competitive products for stand-alone PV power systems. A few megawatt-sized, utility-connected, PV installations, made possible by Government sponsorship and tax incentives, have demonstrated the technical feasibility and excellent reliability of large, multimegawatt PV power-generation plants using crystalline silicon solar cells.

Major FSA Project Accomplishments

- Established basic technologies for all aspects of the manufacture of nonconcentrating, crystalline-silicon PV modules and arrays for terrestrial use. Module durability also has been evaluated. These resulted in:
  - Reducing PV module prices by a factor of 15 from $75/W$_p$ (1985 dollars) to $5/W$_p$ (1985 dollars).
  - Increasing module efficiencies from 5 to 6% in 1975 to more than 15% in 1985.
  - Stimulating industry to establish 10-year warranties on production modules. There were no warranties in 1975.
  - Establishing a new, low-cost high-purity silicon feedstock-material refinement process.
  - Establishing knowledge and capabilities for PV module/array engineering/design and evaluation.
  - Establishing long-life PV module encapsulation systems.
  - Devising manufacturing and life-cycle cost economic analyses.
- Transferred technologies to the private sector by interactive activities in research, development, and field demonstrations. These included 256 R&D contracts, comprehensive module development and evaluation efforts, 26 Project Integration Meetings, 10 research forums, presentations at hundreds of technical meetings, and advisory efforts to industry on specific technical problems.
- Stimulated the establishment of a viable commercial PV industry in the United States.

Engineering Sciences And Reliability Summary

The Engineering Science and Reliability activities of the Flat-Plate Solar Array (FSA) Project were directed at developing the engineering technology base required to achieve modules that meet the functional, safety, and reliability requirements of future large-scale terrestrial photovoltaic (PV) systems. Key objectives of this activity included: (1) identification of functional, safety, and reliability requirements for such applications; (2) development of the engineering analytical approaches, test techniques, and design solutions required to meet the requirements; (3) synthesis and procurement of candidate module designs for test and evaluation; and (4) performance of testing, evaluation and failure analysis to define design shortfalls and thus areas requiring additional research and development.

In 1975, an important first emphasis of the engineering activity was to determine the detailed requirements that a module must meet to perform cost-effectively in future large-scale power-generation applications. Because such applications did not exist in 1975, the Jet Propulsion Laboratory (JPL) contracted with leading architecture-engineering firms such as Bechtel Corp. and Burt Hill Kosar Rittelmann Associates to develop array concepts for future central-station, residential, and commercial PV systems.

During the studies the contractors developed detailed module functional requirements for each application, assessed various operation and maintenance scenarios, and identified the implications of applicable building and safety codes and standard construction practices. An important finding from these early studies was that existing electrical safety codes were inappropriate for PV systems because of the inability of a PV system to be turned off and the inability of solar cells to provide the high short-circuit currents needed to activate normal fuses and circuit breakers. Underwriters Laboratories, Inc. (UL) was subsequently contracted with to develop the needed technologies including detailed safety system concepts and safety construction requirements for PV modules. During the life of the Project, UL's research led to Article 690 (Solar Photovoltaic Systems, in the 1984 National Electrical Code), and to UL Document 1703, defining detailed requirements for UL listing of PV modules for electrical safety.

In parallel with the contracted requirement-generation efforts, JPL in-house activities quantified the environmental weather stresses that would be encountered by a module during 20 to 30 years of field exposure. Important accomplishments included definition of module hail-impact probabilities, operating temperature levels, soiling levels and ultraviolet exposure levels. In another contract, the Boeing Engineering and Construction Company developed detailed data on array wind pressure loading levels including considerations of array structural flutter.

As the engineering requirements were definitized, additional engineering research was conducted to develop ways of satisfying the requirements. Important research was conducted to define optimum array structural configurations, determine optimum installation, maintenance, and replacement strategies, and identify needed electrical safety, fire safety, wiring, and module interconnection technologies. Important analytical and test methods were developed for achieving optimum module thermal designs, optimum series-parallel array circuit designs, and optimum array-load electrical control strategies. A necessary part of defining cost-effective solutions was to reconcile and iterate initial goals with the realities of available technologies used in the most cost-optimum manner. When available technologies fell short, they were highlighted for continued research.

Achieving the engineering technologies required for 30-year life was another important thrust of the FSA engineering activities. During the 11-year Project life, reliability-physics studies developed definitive design data and analysis and test methods in the following areas:

- Interconnect fatigue.
- Optical surface soiling.
- Hail-impact resistance.
- Glass-fracture strength.
- Cell-fracture strength.
- Cell temperature-humidity endurance.
- Module temperature-humidity endurance.
- Hot-spot heating.
- Bypass diode reliability.
- Electrical breakdown of insulation systems.
- Electrochemical corrosion.

Based on these technologies, together with the development of improved module encapsulants within the FSA Encapsulation Task, module lifetimes increased from 1 or 2 years in the mid 1970s, to lifetimes of 20 to 30 years at the end of the Project.

To measure module cost and performance, and provide modules for use in application experiments, the engineering activity conducted a series of module purchases from industry starting in 1975. This module procurement activity played a central role in the Project by providing a conduit for the transfer of cell and module technologies to the manufacturers and for the identification of design shortfalls requiring continued research. More than 30 different module designs containing the latest state-of-the-art technologies were procured from industry in a series of five block buys conducted between 1975 and 1981. Each module design was required to meet detailed specifications for safety and reliability and was tested against these requirements in an extensive qualification testing program. During the course of the Project, the JPL module design specifications achieved widespread international acceptance and use in the procurement of PV modules and systems.

In support of the block procurements, the module quality assurance and failure analysis activities played important roles in the quantification of design deficiencies and in the determination of the exact causes of observed failures. During the period of the Project, failure analyses were conducted on more than 400 module designs in the process of investigating 1200 reported design problems. Important progress also was made in the development of electrical measurements, environmental testing, and failure analysis technologies. Many of the measurements and testing technologies have found their way into national and international consensus standards.

By the close of the Project, state-of-the-art modules were being successfully integrated into numerous residential and multi-megawatt central-station applications, thus validating the requirements and technologies developed. Life-test data on these modules suggest that the best should have lives on the order of 20 to 30 years.

In addition to providing a detailed overview of the FSA engineering activities and accomplishments, this volume contains a detailed Bibliography (Appendix A) containing references to 350 published works documenting the details of the technologies developed.

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SECTION I
Introduction

A. HISTORICAL OVERVIEW

At the start of the Flat-Plate Solar Array (FSA) Project, originally known as the Low-Cost Silicon Solar Array (LSSA) Project, the program recognized the need for a function to define the detailed technical requirements of photovoltaic (PV) modules to be used in future large-scale terrestrial energy-generation applications. Such a requirement-generation activity was implemented to focus the technology development activities toward the critical technical requirements of future PV applications, thereby expanding upon the earlier defined module cost, efficiency, and lifetime requirements. The need for a testing and evaluation function also was recognized and implemented at the beginning of the Project. The purpose of this function was to measure the progress of the technology development activities. The instrument that enabled the measurement of progress was the procurement of a broad variety of modules for qualification testing, field testing, and failure analysis. The acquired performance data played a central role in focusing the subsequent development of many engineering and reliability technologies needed to achieve the module performance required for the future PV applications.

In 1975, when the Project began, the above described functions originated as the Design and Test and Large-Scale Production Activities noted in Figure 1. Subsequently, the Design and Test Activity became the Engineering Area, and then the Engineering Sciences Area, as the importance of developing the PV engineering technology base was recognized as a task comparable in importance to development of solar cell materials and processing technologies. The early Large-Scale Production Activity evolved into the Operations Area and then into the Module Performance and Failure Analysis (MPFA) Area as the function of buying large numbers of modules for demonstration projects and application experiments was transferred to other U.S. Department of Energy (DOE) laboratories. The JPL activity then concentrated on procurements of developmental module designs for qualification testing, performance measurement, and failure analysis. In 1983, the Engineering Sciences Area, the MPFA Area, and the Encapsulation Task* were merged to form the Reliability and Engineering Sciences Area. The merger reflected the increasing role of reliability research and the close tie between reliability research, encapsulant development, and module testing activities.

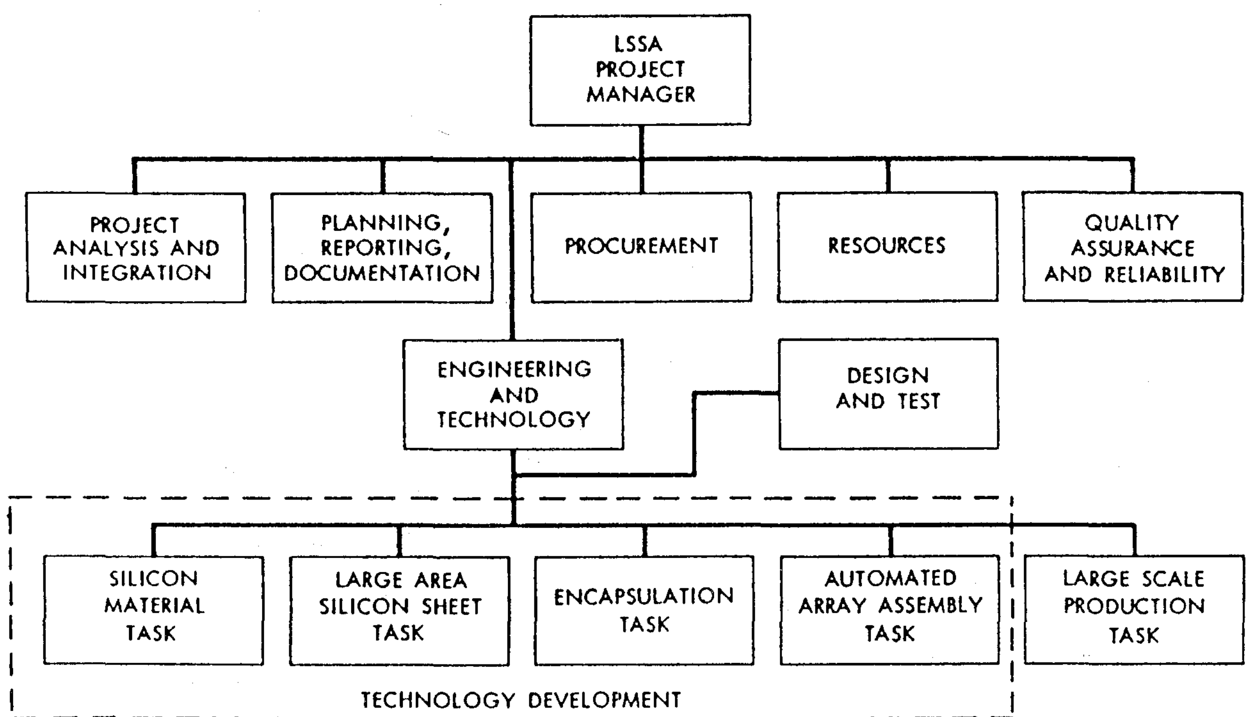


Figure 1. Low-Cost Silicon Solar Array Project 1975 Organization Chart

*The history and accomplishments of the Module Encapsulation Task are described in Volume VII of this report sequence.

Organizational Approach

From the beginning of the Project, engineering, testing, and evaluation activities were closely integrated and performed as the closed-loop development process shown in Figure 2. In this process, engineering requirements for PV modules intended for future large-scale applications were developed through a research activity that heavily involved industry organizations that were expert in the application sectors identified as important future large-scale markets (References 1 through 3).

The Jet Propulsion Laboratory (JPL) researchers developed detailed environmental test requirements to definitize the 20-year life project reliability goals (References 4 and 5). As requirements evolved, they were published in interim design specifications and used to procure modules in a series of five block buys from industry; each module design was required to employ the latest state-of-the-art technologies. The module block-buy procurements served as effective vehicles for transferring the requirements to module manufacturers, and assessing the implications of the requirements on module performance and cost (References 6 and 7).

Module procurements also enabled close collaboration between manufacturers and JPL researchers developing module technologies and conducting evaluation testing and failure analysis. Thus, JPL researchers gained data to identify research priorities as manufacturers also received information on the latest module technologies being developed under the FSA Project.

After successfully passing the JPL Qualification Tests, most module designs were manufactured in modestly large quantities sufficient for fielding and evaluation in one or more DOE application experiments ranging from 1 kW to 1 MW (Reference 8). Performance data from these application experiments were invaluable in validating or suggesting changes to the JPL module design requirements and to the module designs themselves. The feedback of field and qualification test data is schematically illustrated in Figure 2.

A key element of the feedback process was detailed analysis of module failures observed to occur at any point in the development process, from early developmental testing to field applications (References 9 and 10). This function was built upon a previously existing JPL failure-analysis capability devoted to performing detailed analyses of spacecraft parts failures. The function was instrumental in accurately identifying the exact cause of failures so that research activities could be focused in the proper areas.

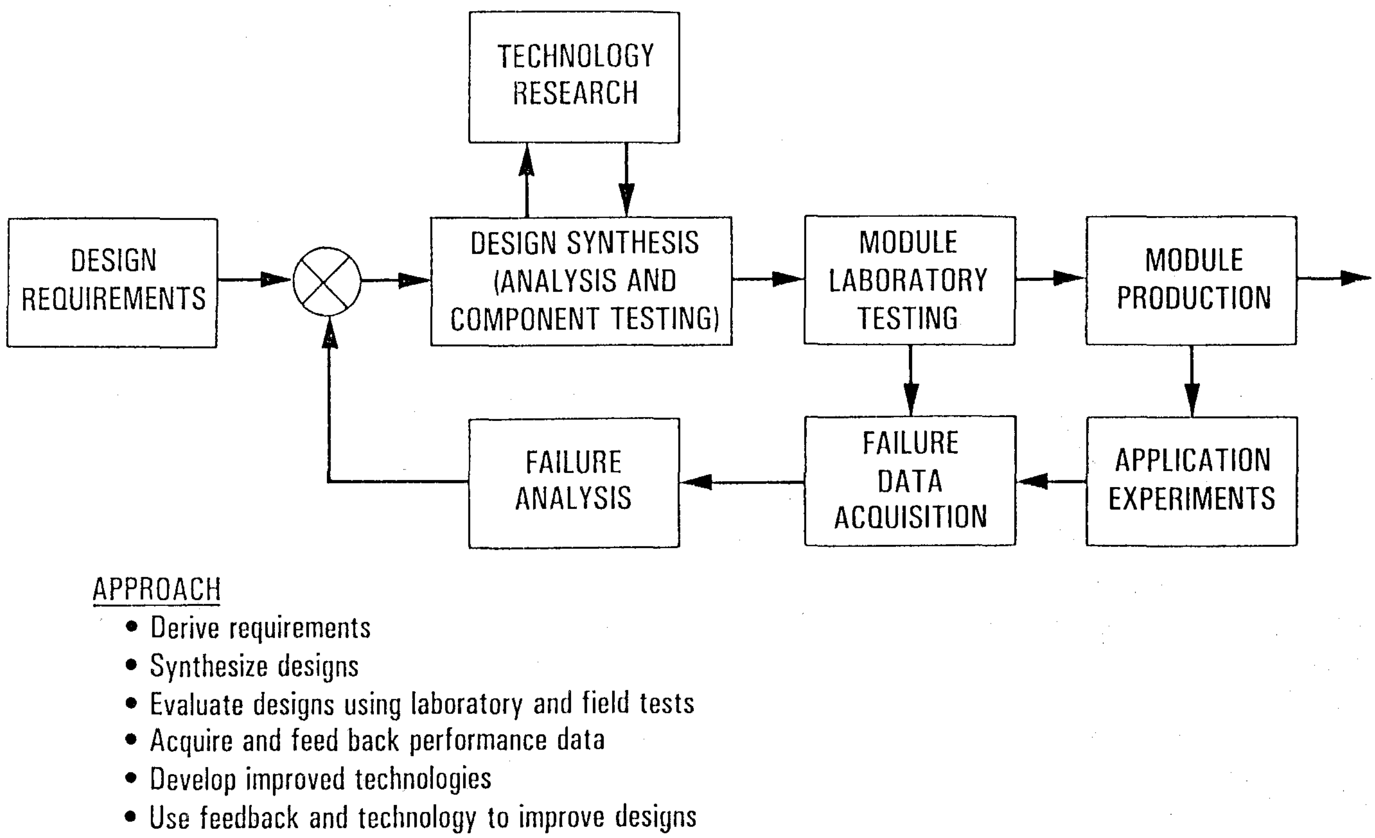


Figure 2. Module and Array Research Approach

Although the engineering and testing function of the Project originally was thought to offer little in the way of contributions to technology development (see Figure 1), the results of early module testing and redesign soon indicated a substantial need for improved engineering technologies in the areas of reliability and safety design and in the development of testing and measurement methods. Thus, research of engineering sciences and reliability technologies became a major thrust as the Project matured and module designs became increasingly more sophisticated for large, high-voltage, central-station applications (References 11 through 15).

B. DOCUMENT ORGANIZATION

The remainder of this document is divided into four sections that deal with details and accomplishments of the activities described above. These include Generation of Module Engineering Requirements, Engineering Research, Reliability Technology Development, and Module Development and Testing. Together with extensive referencing within the body of these sections, Appendix A includes a complete bibliography of all published work resulting from this research. The Bibliography is subdivided by topical subject as a partial guide to the contents of each reference. Appendix B provides guidelines for acquisition of the references.

SECTION II

Generation of Module Engineering Requirements

A. BACKGROUND

At the start of the FSA Project, the definition of module development goals was limited to cost ($0.50/$W_p$), minimum efficiency (>10%), and useful life (20 years). Undefined were detailed requirements specifying the environments in which the module must survive, application requirements such as mechanical and electrical interfaces, institutional constraints such as building codes and industrial practices, and safety issues. Although future applications had been hypothesized in artist-renditions (Figure 3), it was clear that technology developments would have to be guided by an accurate picture of the requirements for end-use applications if the National Photovoltaics Program was to be a success. An important program risk was that a significant requirement, such as product/application safety, could jeopardize the program if not systematically factored in at the beginning.

In 1975, to define future cost-effective applications, the DOE National Photovoltaics Program established a Photovoltaic Systems Definition function at Sandia National Laboratories in Albuquerque, New Mexico, and a Mission Analysis function at Aerospace Corp. in Los Angeles, California. These two organizations conducted in-house analyses and contracted with leading systems organizations such as General Electric (GE), Westinghouse, and Spectrolab (a leading manufacturer of early terrestrial PV systems) to define future large-scale PV applications and optimum PV systems for each application (References 16 through 18). Architecture-engineering firms, such as Bechtel Corp. and Burt Hill Kosar Rittelmann Associates, were brought in by GE, Westinghouse, and Spectrolab to assist in the system definition studies.

FSA engineering personnel closely followed the progress of these studies to gradually assemble needed insight into the important application demands on future flat-plate PV modules and arrays. Typical findings from these studies included optimum operating voltage levels for various types of systems, inferences on important institutional constraints such as building and safety codes and labor practices, and conceptual designs for array fields in residential, commercial, and central-station applications.

In a parallel effort, FSA engineering personnel made an extensive tour of existing small-remote PV systems deployed in the early 1970s by budding terrestrial PV manufacturers. Figure 4 shows one of the early navigational aides that used 2 x 2 cm space solar cells in an expensive, but reliable glass-silicone rubber module. Discussions with users and maintainers of these small systems, and firsthand evidence of the disrepair and poor construction of many of the systems provided invaluable insight into the need for both enhanced reliability and improved user-interface issues such as maintenance practices and array assembly methods.

The insights gained from these early encounters with existing small, remote applications as well as from

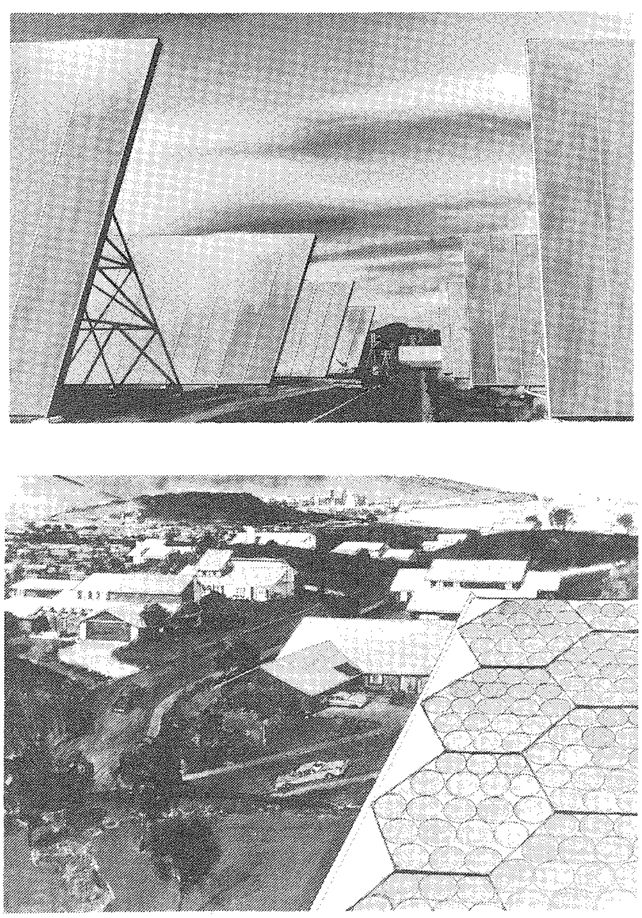


Figure 3. Artist's Early Renditions of Future Large-Scale PV Applications

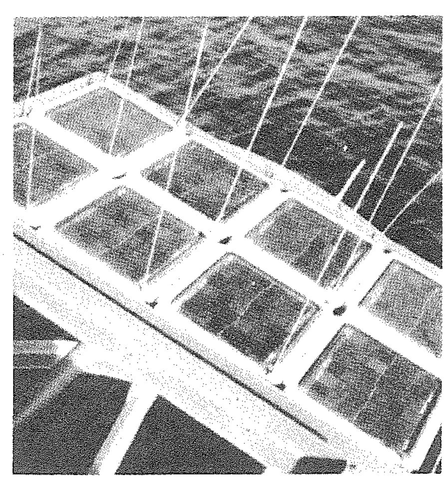


Figure 4. Navigational Buoy PV Application of 1975 Time Period

conceptual designs for future large-scale applications, served to focus much of the requirements-generation research that followed. JPL's philosophy and experience with the definition of functional and environmental requirements for spacecraft missions provided an encouraging in-house institutional environment for the conduct of the work, despite early industry sensitivity to the "aerospace approach" to requirement generation, and the inferred adverse implications on product cost. In the end, JPL requirements have been adopted internationally and are considered to have been highly instrumental in developing the excellent worldwide reputation of the present line of commercial low-cost PV products.

B. APPLICATION REQUIREMENTS RESEARCH

In response to the need for definitive requirements to guide the development of PV modules toward the needs of future large-scale applications, research contracts were initiated with leading industrial teams. These teams not only were knowledgeable of future PV systems concepts through involvement with the Sandia systems studies, but also were in a position to apply their corporate expertise to identify and develop detailed guidelines for flat-plate modules and arrays. Bechtel Corp. of San Francisco contributed extensively to the early definition of guidelines for optimum modules and arrays for central-station applications (References 1 and 19). Similarly, Burt Hill Kosar Rittelmann Associates defined guidelines for residential and commercial applications including consideration of applicable building and safety codes and labor practices (see References 2 and 3).

Although building codes were not found to pose a significant constraint on the design of PV arrays, existing standard safety practices associated with typical high-voltage AC electrical systems were found to be inconsistent with the safety attributes of photovoltaics. This absence of applicable safety codes and design practices was identified as a significant problem. Unlike conventional electrical sources, PV modules cannot be turned off and they cannot generate the overcurrent needed to blow fuses and circuit breakers in the event of a short circuit or short to ground. To develop the needed safety technology, JPL contracted with Underwriters Laboratories, Inc. (UL) to develop detailed module safety requirements and conceptual approaches to the entire electrical safety system for a complete PV power system (Figure 5). On the basis of this work, requirements for a UL listing of modules were developed (References 20 through 22) and a new Article 690, covering required electrical safety features in high-voltage PV power systems, was included in the 1984 revision of the National Electrical Code (NEC) (Reference 23). Detailed requirements were also generated by UL for array wiring techniques and allowable wire types (Reference 24).

General product liability issues also were researched by Carnegie-Mellon University to further identify implications that should be incorporated in the module development process (Reference 25).

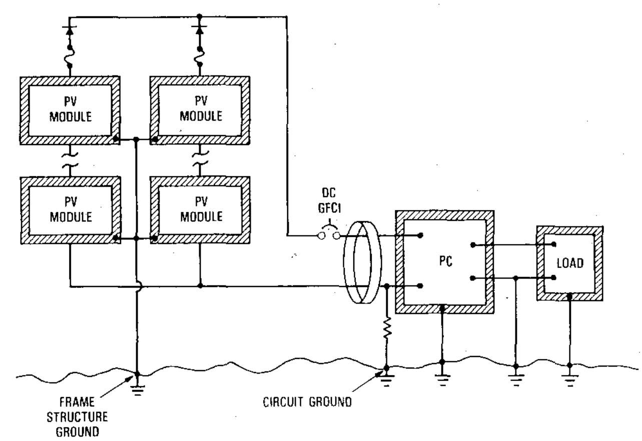


Figure 5. Schematic Diagram of Electrical Safety Features of a PV Power System

C. ENVIRONMENTAL REQUIREMENTS RESEARCH

In parallel with research to define requirements associated with the integration and use of PV modules in future large-scale applications, a substantial research thrust also was mounted to understand and quantify the environmental loads and stresses that a PV module and array must withstand in the outdoor weathering environment.

Use of crystalline-silicon solar cells in space had demonstrated that PV power systems were a practical and reliable method of generating electrical power. Environmental requirements of the proposed terrestrial applications, however, were significantly different from those of the vacuum environment of space. In addition to the ultraviolet (UV) and thermal environments of space, terrestrial modules had to deal with a host of moisture-related weathering phenomena: wind, hail, salt fog, airborne soiling, and chemical reactivity with the constituents in our air.

One element of controversy that entered early into the definition of environmental requirements was the trade-off between the design of a high-reliability, long-life product and one that was inexpensive and replaceable. Important considerations included such items as the service environment and expected duration of the intended application, expected future cost reductions or product obsolescence, ease and cost of periodic maintenance and replacement, and consistency of the product's reliability with the manufacturer's image and reputation.

The approach taken was not only to investigate the expected environmental stress levels and their probabilities, but also to study their implications on module design, manufacturing costs, and the life-cycle cost of electrical energy from the total PV system. This led to the need to understand, in detail, the technology required to survive the various field stresses and to predict the reliability and life of a given design. It also required development of tools to understand the impact of individual module failures on system life-cycle energy costs including considerations of optimal repair and replacement. The above research activities resulted in substantial engineering technology developments described in later sections of this report. A key point is that the derived environmental requirements did not result from an autonomous environmental requirements development activity, but rather from an integrated systems engineering analysis of the optimum levels of environmental durability from the point of view of a life-cycle system cost. They were built upon an extensive engineering-sciences and reliability-research activity to define the fundamental relationships between technology attributes and field-life and reliability.

1. Environmental Stress Characterization

During identification of the important application-dependent and site-dependent stresses, difficulty was encountered in reducing them to specific stress-time requirements against which modules could be designed and verified. Some environments, such as system voltage level, were easily quantified. Others, such as temperature and humidity extremes, and maximum wind velocity, required historical weather data and considerations of statistical likelihood over the design-life of an intended application.

One of the more extensive analyses of the natural environment dealt with definition of the probability of being struck by large hailstones in different regions of the United States (References 26 and 27). This effort integrated historical hail-impact data with a unique statistical analysis to predict probability of impact as a function of hailstone size and module area.

One environment that eluded accurate quantification is the integrated UV flux level seen by a PV module during the course of its life. Although early research scoped the nature of the problem and developed rough estimates of UV flux levels (Reference 28), accurate determinations would require in situ measurements during extended periods at a variety of sites in the United States. This level of effort was beyond the scope of the program. Some point measurements were made, however, of terrestrial UV spectral irradiance levels, and accelerated UV test apparatuses were accurately characterized (Reference 29).

The most useful characterizations of temperature, humidity, and solar irradiance levels were achieved using computer simulations of operating conditions based on Solar Radiation-Surface Meteorological Observations (SOLMET) (References 30 and 31) hourly weather data for sites in the United States. These computer simulations were used in a variety of reliability life-prediction studies (References 32 and 33) and array performance characterization studies (References 34 and 35). In one novel analysis (References 36 and 37), hourly data that spanned a time period of more than 20 years were used to characterize the statistical likelihood of daily, weekly, and monthly average solar-irradiance levels lying below those defined by historical monthly average values for a variety of sites in the United States. This cloudy-day statistical analysis was developed to assist in determining the optimum energy-storage requirements for stand-alone PV systems.

Figures 6 and 7 provide summary data descriptive of the range of irradiance levels and module operating temperatures encountered during periods of significant PV energy production (see Reference 34). Similar data also were generated characterizing the fraction of energy generated versus angle of incidence (Reference 38) and solar spectrum (Air Mass) (Reference 39).

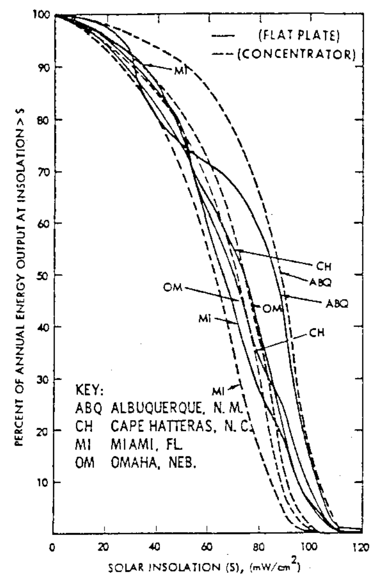


Figure 6. Statistical Relationship Describing the Fraction of Annual PV Energy Generated During Periods When the Solar Irradiance is Above a Specific Level

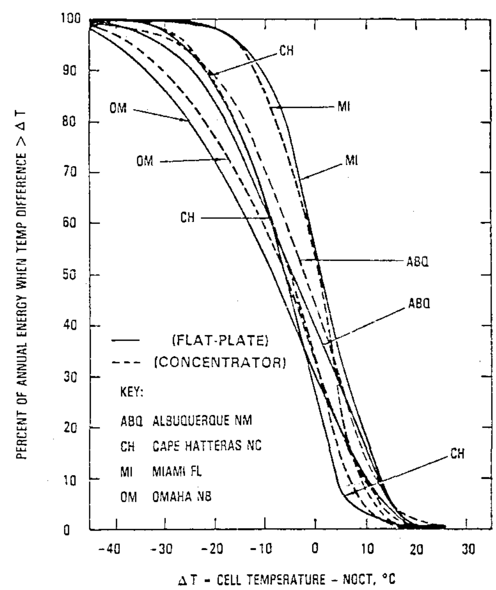


Figure 7. Statistical Relationship Describing the Fraction of Annual PV Energy Generated During Periods When the Solar Cells are Operating at a Given Temperature or Higher

2. Qualification Tests

Analytical stress-time models and site weather characterizations were found very useful in life-prediction simulations, but they failed to provide quick and inexpensive tests for a fabricated module. This need was met by development of module qualification tests. During the 11 years of the FSA Project, several module qualification tests were developed and refined (References 4, 5, and 40), and used extensively in the block-buy module procurements described in Section V of this report. Table 1 lists the six design and test specifications that detail the qualification test procedures used in the five block procurements and in a sixth procurement of modules for an extensive set of DOE application experiments constructed via a Program Research and Development Announcement (PRDA) in 1980. Table 2 lists the qualification tests associated with the latest, Block V, Specification (Reference 41).

Table 1. Project Module Design and Test Specifications

Block I:	5-342	First Generation	Oct 75
Block II:	5-342-1B	Second Generation	Dec 76
Block III:	5-342-1C	Second Generation Update	May 77
PRDA 38:	5101-65	Intermediate Load Center	Oct 77
Block IV:	5101-16A 5101-83	ILC (Third Generation) Residential (Third Generation)	Nov 78 Nov 78
Block V:	5101-161 5101-162	ILC Applications Residential	Feb 81 Feb 81

Table 2. Project Block V Module Qualification Tests

Test	Level and Duration
Temperature cycling	200 cycles; each cycle: 4 h, −40°C to +90°C
Humidity-freeze	10 cycles; each cycle: 20 h at 85°C, 85% RH followed by 4 h excursion to −40°C
Cyclic pressure loading	10000 cycles, ± 2400 Pa (± 50 lb/ft^2)
Wind resistance (shingles only)	Underwriters Lab Standard UL 997 1.7 k Pa (35 lb/ft^2)
Hail impact	10 impacts at most sensitive locations using 25.4 mm (1 in.) iceball at 23.2 m/sec (52 mph)
Electrical isolation	Leakage current ≤50 μA at twice worst-case system open circuit voltage plus 1000 V
Hot-spot endurance	3 cells back-biased to maximum bypass-diode voltage and cell-string current for 100 h of on-time

Development of the qualification tests was one of the important focuses of the reliability research activity described in Section IV of this report. In addition to development of the test procedures themselves, an important contributor to the definition of environmental test levels was the feedback of field-reliability performance data from the many systems fielded by the Systems and Applications portion of the DOE National Photovoltaics Program. During the years of the Project, the environmental requirement levels continually were refined so as to fail module designs that exhibited unacceptable field reliability while passing module designs with good field performance. Lessons learned from the qualification test development effort have been documented for application by those developing new thin-film modules or by other interested users (Reference 42).

D. SOLAR ARRAY MEASUREMENTS AND TESTING STANDARDS

Early in the history of the National Photovoltaics Program, it was recognized that the development of measurement and testing standards was necessary for accurate communication of performance goals and progress among PV researchers. While developing module requirements for the block-buy procurements, a substantial effort was made to standardize array nomenclature, electrical efficiency definitions (Reference 43), and performance measurement methods (Reference 44).

Throughout the FSA Project, engineering personnel played an active role in the development of performance measurement techniques (References 45 and 46) and rating methods (References 34, 47, and 48), and served on a wide variety of concensus standards committees.

In 1978, DOE established a collaborative Performance Criteria and Test Standards Project involving the Solar Energy Research Institute (SERI), JPL, the Massachusetts Institute of Technology (MIT), and Sandia National Laboratories (References 49 and 50). The objective of the Project was to provide standardization across the DOE program and to generate measurement and testing approaches for consideration by private consensus standards organizations such as the American Society for Testing and Materials (ASTM) and the Institute of Electrical and Electronics Engineers, Inc. (IEEE). The Project was initiated in response to Legislative directives of the Photovoltaic Research, Development, and Demonstration Act of 1978 (P.L. 95-590) that required the DOE to develop and publish performance criteria for PV energy systems. Building on its work related to the block procurements, JPL managed the generation of performance criteria and test methods for modules and arrays, while Sandia managed the work related to the overall PV system, and MIT managed the work on power conditioning and storage (see References 34 and 35). SERI coordinated the entire Project and integrated the various results into a comprehensive two-volume document that represents the contributions of more than 100 experts in photovoltaics and related technologies (Reference 51).

E. SIGNIFICANT ACCOMPLISHMENTS

Specific design data and recommendations that evolved from the engineering requirements activity include:

(1) Detailed assessments of residential and commercial building codes and their implications for the use of photovoltaics.

(2) Detailed assessments of utility design and construction practices and the implications for their use of photovoltaics.

(3) Module electrical safety design requirements and practices (UL 1703).

(4) Safety system design concepts and recommendations (National Electrical Code Article 690).

(5) Array wire selection and safety design guidelines.

(6) Module product-liability guidelines.

(7) Module design specifications including environmental endurance test requirements.

(8) Hail-impact probability data and statistical analysis methodology.

(9) Cloudy-day statistical analysis methodology and solar irradiance deficit data.

(10) Energy performance estimation techniques based on Nominal Operating Cell Temperature (NOCT).

SECTION III

Engineering Research

During the course of the FSA Project, several important technology gaps were identified relating to needed, but unavailable engineering analysis and test methods and data defining the functional interfaces for flat-plate modules intended for future large-scale PV applications. If low-cost modules were to lead to low-cost PV systems, they also had to be consistent with low array costs, including structures and wiring, and with low installation and maintenance costs. The engineering research approach described in this section was to study the module in the context of the complete array so as to understand how its electrical circuit and mechanical design affected the life-cycle economics of the total array. Minimizing the total array life-cycle costs led to the definition of needed module design attributes, and to the development of important analytical approaches to array optimization.

The following paragraphs describe the technology developments in each topical area of engineering research. These include:

(1) Module and Array Structures Research

(2) Installation, Maintenance, and Replacement Studies

(3) Thermal Design Studies

(4) Safety Technology Development

(5) Electrical Circuits

(6) Electrical Components

(7) Array-Load Interface Characterization

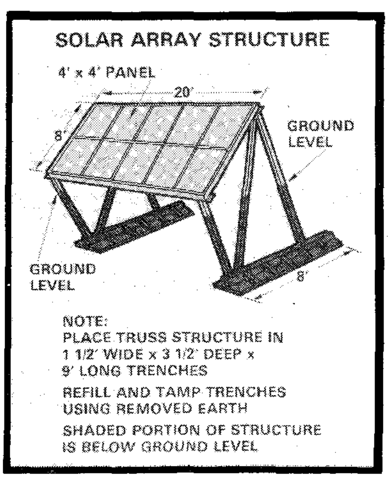
A. MODULE AND ARRAY STRUCTURES RESEARCH

Early PV systems studies indicated the structural elements of modules and arrays (module/panel frames, field support structures, and foundations) would represent approximately 30% of the installed cost of future, low-cost, large-scale PV applications. This early conclusion has proven correct and required that module and array structures be carefully researched to achieve minimum cost designs consistent with application constraints.

Early in the program, JPL contracted with Bechtel Corp. to study array structural cost sensitivities to define optimum array concepts for utility-scale, ground-mounted arrays, and to define cost drivers amenable to reduction through research (References 1, 19, and 52). Bechtel identified the presence of a high cost sensitivity to PV module size (larger is lower cost) and wind loading level, and a low sensitivity to array structural configuration details. Foundations were highlighted as a major cost driver, as were uncertainties in wind loading forces.

The above studies led to several follow-on activities, funded by both JPL and Sandia Laboratories, to develop low-cost, ground-mounted, array structures (References 53 through 58). An example is the foundationless, ground-mounted array concept (Figure 8) developed by JPL engineers (see Reference 56): this concept used rolled sheet-steel frame members and frameless modules for the first time.

To reduce uncertainties in wind loading levels, JPL contracted with Boeing Corp., in conjunction with Colorado State University, to develop both the tools necessary to convert from maximum design wind speed to



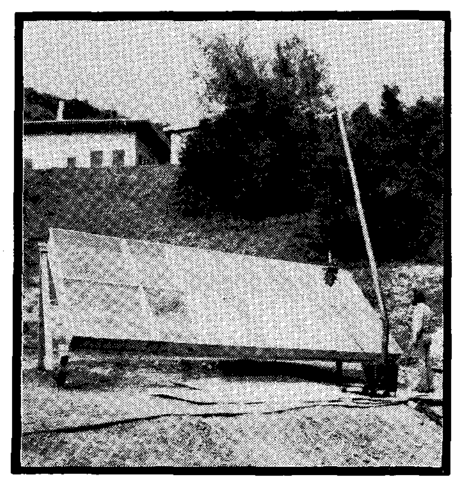



Figure 8. Foundationless Ground-Mounted Array Concept and Prototype Undergoing Structural Testing at JPL

array-pressure loading, and to assess cost-effectiveness of wind-barrier fences. They conducted both analytical studies and wind tunnel test programs, and provided definitive data on the relationship between wind velocity and module and array structural loads including considerations of structural flutter (Reference 59).

In the early 1980s, with the increased programmatic emphasis of residential arrays, several studies also were conducted to develop low-cost roof-mounted arrays. Building on the early work of Burt Hill Kosar Rittelmann Associates (see Reference 2), these studies examined all aspects of residential roof-mounted arrays including design requirements, installation and maintenance practices, and electrical circuit design. The research developed several roof-mounted array concepts and highlighted key cost trade-offs such as reducing the cost of a conventional roof by replacing its watershedding function in the area of the array (References 60 through 64).

In a parallel effort, Burt Hill Kosar Rittelmann Associates also examined arrays for commercial/industrial applications (see Reference 3).

B. INSTALLATION, MAINTENANCE, AND REPLACEMENT STUDIES

Installation, maintenance, and replacement of modules in the field was an area of early concern in life-cycle cost studies of PV plants and, to some extent, remains an issue yet to be totally resolved. Aside from the subject of module failure rates and usable life (discussed in Section IV), an important ingredient in plant installation, operation, and maintenance costs is the level of modularity, the ease of assembly-disassembly of PV modules, and the place of assembly-disassembly (factory versus field). These considerations create a cost sensitivity to module size and electrical and mechanical attachment method that must be factored into the module design. Data on the cost of typical installation, maintenance, and replacement actions also were needed to allow system-level optimizations to be conducted, and module reliability targets to be generated.

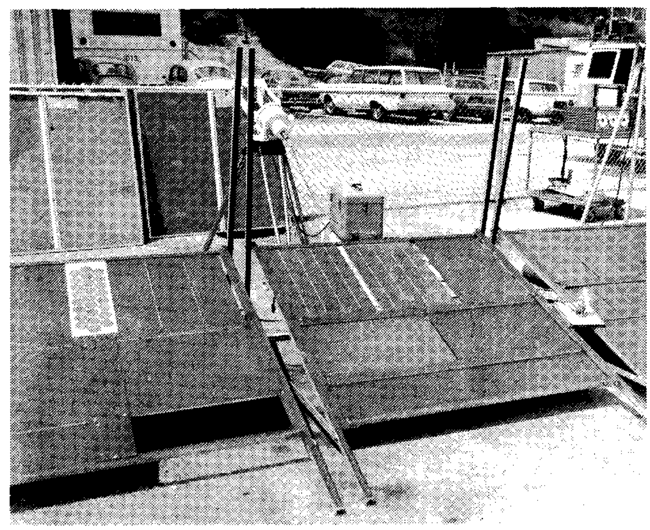
Bechtel Corp. and Burt Hill Kosar Rittelmann Associates, as part of their JPL contract activities, studied various installation, maintenance, and replacement scenarios and developed detailed cost estimates for the preferred least-cost approaches (References 1 through 3, 52, and 65). They also explored methods for washing arrays in central-station and residential-roof settings and made detailed estimates of array-washing costs and the cost-effectiveness of washing (see References 1 and 65). One result of these studies was the identified need for quantitative data on expected field-soiling levels of PV modules. This led to the soiling investigations described in Section IV of this report.

C. THERMAL DESIGN STUDIES

At the beginning of the Project, array operating temperature was identified as an important issue because of its direct influence on the electrical efficiency of solar cells. Electrical power output and voltage of crystalline-silicon solar cells drops at a rate of approximately 0.5% for each 1 °C increase in operating temperature.

Early JPL thermal analyses and field tests (Figure 9) identified key parameters controlling module cell temperature. This led to the development of the Nominal Operating Cell Temperature (NOCT) test procedure for accurately quantifying module cell temperature (References 66 through 68).

A module's NOCT is the temperature the cells attain in an external environment of 80 mW/cm^2 irradiance, 20°C air temperature, and 1 m/s wind velocity. This environment was chosen so that the annual energy produced by a module is well approximated by its efficiency at NOCT times the number of kilowatt-hours per



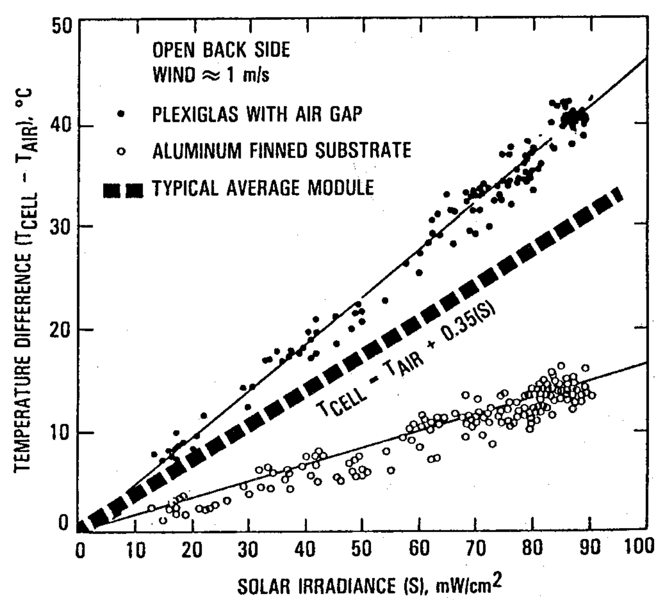


Figure 9. Early Thermal Testing and Typical Thermal Performance of Flat-Plate PV Modules

year of irradiance incident on the module at the site of interest (see References 34 and 47). Typical values of NOCT range from about 48°C for ground-mounted arrays to 60°C for roof-mounted arrays with insulated rear surfaces. Based on the functional dependence suggested in Figure 9, cell temperature was found to be well characterized by the simple expression:

$$T_{cell} = T_{air} + \left(\frac{NOCT-20}{80}\right) S$$

where:

T_{cell}, T_{air}, NOCT are °C; $S = \frac{mW}{cm^2}$

The NOCT concept was developed to provide a convenient means to quantify a module's thermal design and to provide a meaningful reference temperature for rating power output (see References 34 and 66). The procedure has subsequently been adopted internationally.

From the beginning of the DOE PV program, various studies also examined the feasibility of combining PV collectors with flat-plate heating and cooling collectors. The concept was to simultaneously generate hot water (or hot air) and electricity. Although a subject of much debate and analysis, this concept never was reduced to commercial practice for a variety of reasons, including:

(1) Photovoltaics achieves its maximum efficiency and weathering endurance when maintained as cool as possible, whereas thermal energy is maximized at high temperatures.

(2) Commonly used PV circuit and encapsulation components could not easily survive stagnation conditions. This requires a separate cooling system to be used during periods of low or no solar-heating demand.

To resolve the above difficulties, JPL conducted a variety of analyses of unglazed photovoltaic-thermal (PV-T) collectors (References 67 and 69) and developed PV-T testing procedures in support of its work on performance criteria and test methods (see Reference 51).

In the early 1980s, two occurrences focused increased attention on the thermal design of modules and arrays. First, some residential roof-mounted arrays were found to be operating significantly hotter than others. Second, reliability research had confirmed that module degradation was indeed Arrhenius in nature, with a degradation rate doubling for every 10°C increase in temperature. This implied that an array design that ran 10°C hotter than another could be expected to last only half as long.

Subsequent thermal analysis efforts at JPL developed improved understandings of the complex interrelationship between module temperature and the thermal parameters associated with roof-mounting, such as attic ventilation and module standoff distance (Reference 70).

In later years of the Project, additional thermal studies were conducted to resolve measurement scatter observed in the early defined NOCT test procedure. These investigations focused on the detailed effects of both wind cooling and reflected light on the module rear surface (References 71 through 73). A modified NOCT test procedure (Reference 74) was developed incorporating these improved understandings, and has been proposed as a draft ASTM test method.

D. SAFETY TECHNOLOGY DEVELOPMENT

As described in Section II, Generation of Module Engineering Requirements, a substantial effort was initiated in 1979 to define safety requirements for PV modules through contracts with UL and Carnegie-Mellon University. The requirement-generation activity quickly led to the need for development of module and array technologies capable of meeting the guidelines, for improved understanding of the fundamentals underlying the safety of PV systems, and for data on the safety performance of available modules.

Supporting this activity, UL generated guidelines (see Reference 21) detailing module construction attributes required to satisfy the electrical safety system concepts it was developing. Bechtel Corp., in a parallel study, researched utility safety practices and developed data on the design of electrical insulation systems for high voltage modules (Reference 75). A key finding of the Bechtel study was the poor fundamental understanding of electrical-insulation design and life prediction. This subsequently led to significant JPL research in this area.

In addition to research on electrical safety attributes, JPL initiated a series of tests at UL in 1980 to evaluate the flammability attributes of PV modules and their ability to achieve the Class A and B fire ratings required for high fire-risk applications such as schools and public buildings. During these tests (see Reference 21), it was found that newly developed modules that incorporated polyvinyl butyral (PVB) or ethylene-vinyl-acetate (EVA) encapsulants were unable to achieve these fire-resistance ratings despite their primary construction of glass (Figure 10). JPL subsequently initiated a collaborative research program with module manufacturers and materials suppliers and successfully developed fire-ratable module construction techniques (Reference 76 through 78) as highlighted in Table 3.

E. ELECTRICAL CIRCUITS

A key role of the electrical circuit of a PV array is to reduce the impact on electrical energy generation of individual component failures such as cracked solar cells and fatigued interconnects within modules. Table 4 highlights those failure mechanisms that are affected, either positively or negatively, by the listed circuit features (see Reference 14). Notice that the proper series-paralleling of the circuit requires a balance between enhancing the array's resistance to open-circuit and current-reduction mechanisms, and lowering the

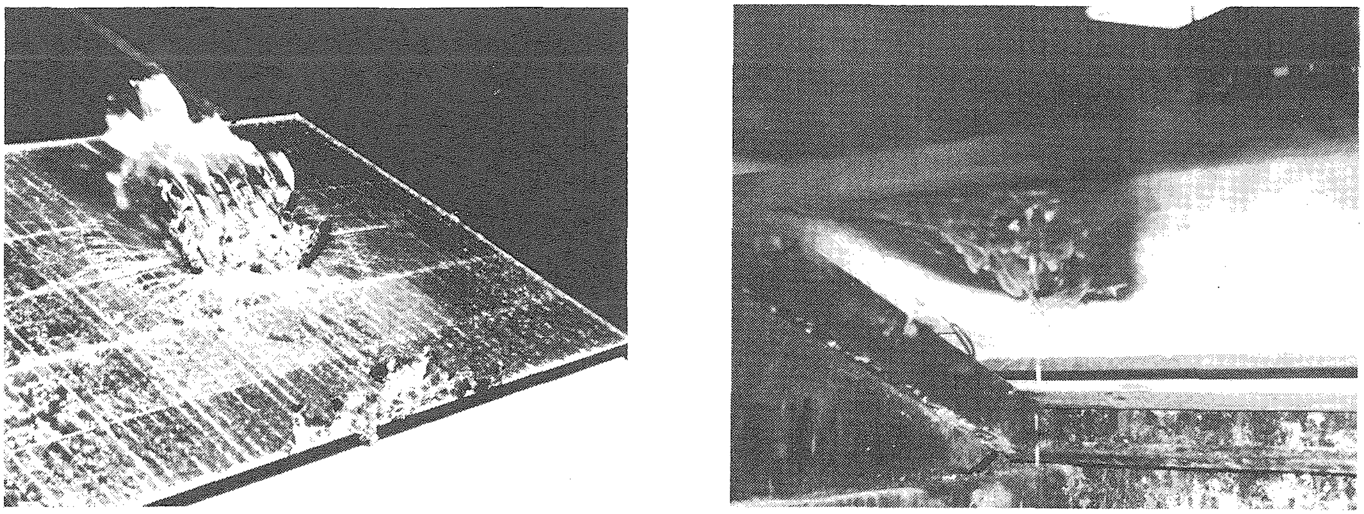


Figure 10. Flaming of Module Rear-Surface Encapsulant During Burning-Brand Flammability Testing of Early PVB and EVA Modules

Table 3. Fire-Ratable Module Constructions

Back-Cover Material Description[a]	Manufacturer	≈ $/ft²
Class B		
Kapton (2 mils)	DuPont 200H	0.75
Vonar/Surmat/Conbond 1560/T (4 mils)	DuPont	–
FG (4 mils) – red silicone rubber (1 side)	3M SRG-0607 1/c	1.08-0.76
FG (4 mils) – Neoprene rubber (1 side)	3M FGN-0605 1/c	0.80-0.64
Mylar/Al (0.7 mils)/rubberized back coat	Spire Block IV	–
Al (3 mils) in 4-layer laminate	–	–
T (1½ mils) – Mylar (5 mils) – Al (0.5 mils) – EVA (4 mils)	Gila River – Solar 2	0.80
T (1½ mils) – FG (8 mils – epoxy) – T (1½ mils)[b]	Gila River – Solar 5	
Class A		
Refrasil (15 mils) – Z-mix (1 side)	HITCO C100-28 w/Z-mix	2.22
FG (24 mils) – Z-mix (1 side)	HITCO 1584 w/Z-mix	1.42
FG (13 mils) – Z-mix (1 side)	HITCO 1582 w/Z-mix	1.12
FG (7 mils) – Z-mix (2 sides)	HITCO Solar-Tex	0.63-0.73[c]
Stainless steel foil (2 mils)	–	0.45

[a] T – Tedlar; FG – fiberglass; Al – aluminum; EVA – ethylene vinyl acetate

[b] Possible candidate for Class A. [c] Price varies according to color: black/black; white/white; black/white

Table 4. Effect of Source Circuit Features on System Energy Loss Caused by Various Failure Mechanisms

Problems	Cell Paralleling	Contact Redundancy	Multiple Interconnects	Bypass Diodes	Cell Circuit Layout	Frequent Cross-Strapping	Ground-Fault Interrupt	Resistance Ground
Shadowed cells	−			−	−	−		
Interconnect fatigue	−		−	−		−		
Open-circuit cells	−	−		−		−		
Shorted cells	+					+		
Mismatched cells	−			−		−		
Ground-fault arc							−	−
In-circuit arcs	−	−	−	−				
Hot-spot heating	+			−		+		

+: Lowered losses
−: Increased losses

array's resistance to shorted cells and hot-spot heating. The use of bypass diodes, however, has a positive effect in every case, but must be balanced against the cost of installing the diodes.

Early in the program, it became obvious that quantification of the implications of component failures on system life-cycle energy cost was critical both to the design of the array's circuit and to optimization of maintenance and replacement options. It also was needed to establish guidelines for allowable component failure rates.

In 1978, a JPL research activity was initiated to develop analytical tools required to compute the effect of statistically small numbers of open-circuit cell failures on system power output, as shown in Figure 11. The analysis was developed parametrically for a broad range of series-paralleling configurations with and without bypass diodes (References 79 and 80).

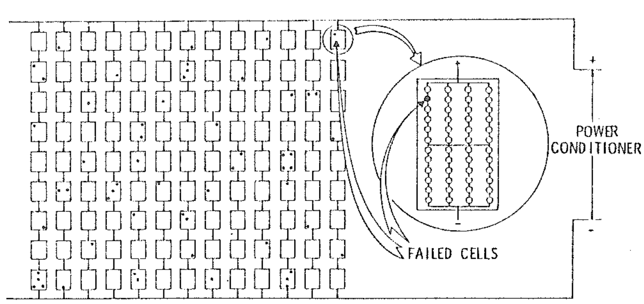


Figure 11. Visualization of Random Cell Failures Throughout a PV Array Field

Figure 12 illustrates the general concept of series-paralleling and bypass diodes, and defines the nomenclature used to quantify various circuit configurations. As shown in Figure 12, each source circuit may contain a single string of series solar cells or several parallel strings interconnected periodically by cross ties. The cross ties divide each source circuit into several series blocks. One or more series blocks also may be bridged by a bypass diode, which is designed to carry the source-circuit current in the event that local failures constrict current flow to the point of voltage reversal and power dissipation.

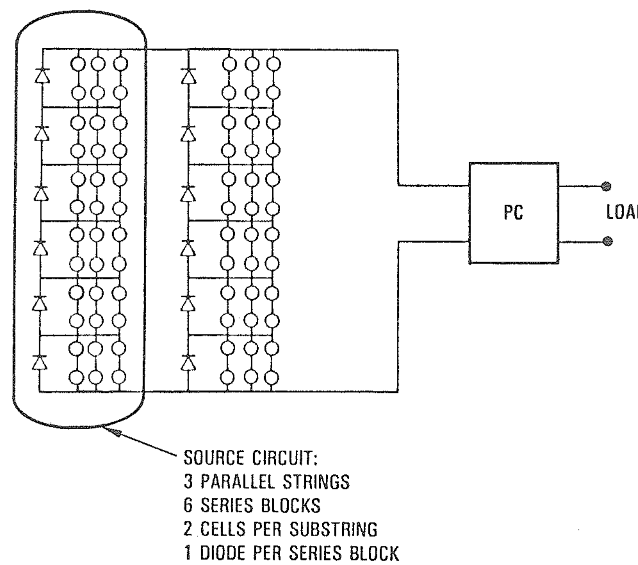


Figure 12. Series-Parallel Circuit Nomenclature

Results of the analysis were a large collection of plots (documented in Reference 80). The plots, as shown in Figure 13, allow rapid computation of effects of cell failures and circuit redundancy on array power loss. An extension of the analysis was completed for shorted cells (Reference 81). Table 5 summarizes the results of the analysis for a 450-V central-station source circuit with a failed-component fraction of 0.05% open-circuit cells, and 0.05% short-circuit cells. It can be seen that optimal tolerance to component failures exists with single-string source circuits with many bypass diodes.

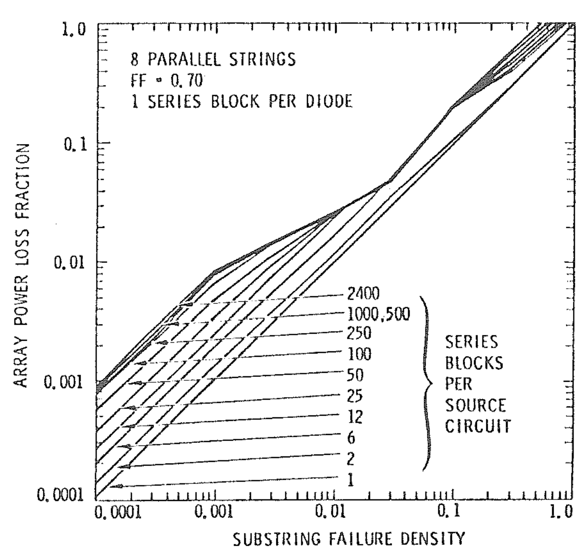


Figure 13. Plot for Power Loss Determination

Table 5. Fraction Power Loss Caused by 0.05% Shorted Cells and 0.05% Open-Circuit Cells for a 450-V (1000 Series Cell) Source Circuit Versus Series-Parallel Configuration, with One Bypass Diode per Series Block

Cells Per Substring	Series Blocks	Cells in Parallel 1	4	8	16
20	50	0.001 0.011 0.012	0.001 0.050 0.051	0.001 0.025 0.026	0.001 0.015 0.016
10	100	0.001 0.005 0.006	0.001 0.022 0.023	0.002 0.013 0.015	0.002 0.008 0.010
5	200	0.001 0.003 0.004	0.002 0.010 0.012	0.002 0.007 0.009	0.002 0.004 0.006
2	500	0.001 0.001 0.002	0.002 0.004 0.006	0.004 0.003 0.007	0.006 0.002 0.008

Optimum Design Region (16 in parallel, 10 cells per substring / 100 series blocks)

Sensitive to Shorted Cells (2 cells per substring / 500 series blocks)

Top Line: Short-Circuit Losses Mid Line: Open-Circuit Losses Bottom Line: Total Losses

In 1979, development of the above circuit-analysis tools allowed, for the first time, prediction of the life-cycle cost impact of various failure mechanisms and rates (Reference 82). A key first use of the analysis, therefore, was to examine the cost effectiveness of various maintenance-replacement strategies based on the replacement cost estimates resulting from the earlier Bechtel studies.

Figure 14 displays the relative life-cycle energy cost for two replacement strategies as a function of the number of series blocks and parallel cells per source circuit. In the first strategy (solid curves), no module replacement is allowed, and it can be seen that life-cycle costs increase sharply with low numbers of series blocks. This reflects the rapid array degradation shown in Table 5 in the same circumstances.

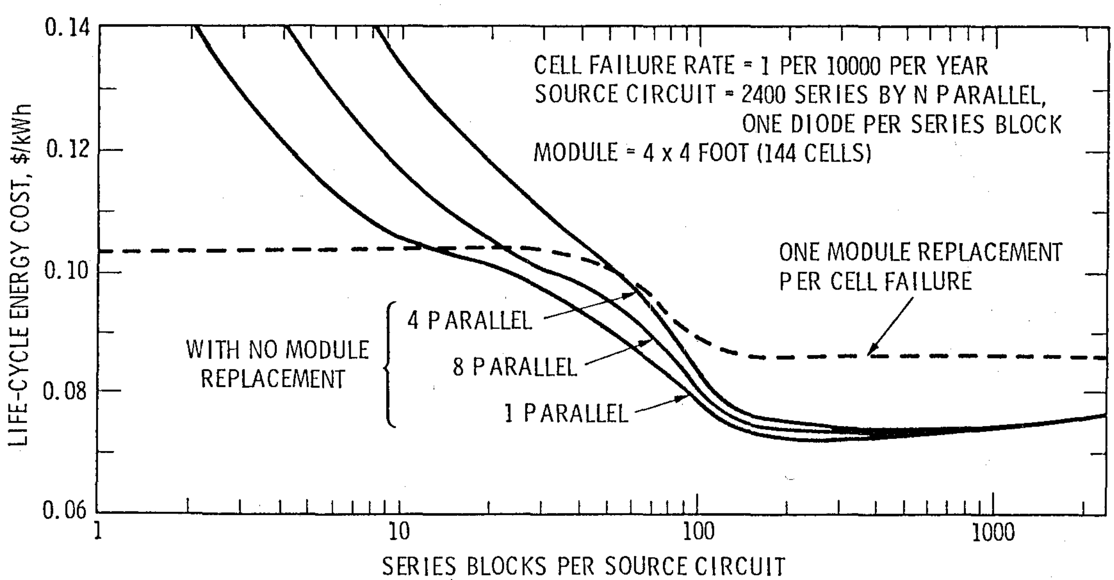


Figure 14. Relative Life-Cycle Energy Cost Versus Series-Paralleling and Maintenance Strategy

For the second strategy (dashed curve) in Figure 14, modules are replaced each time a solar cell fails during the 30-year life of the plant. This results in no power degradation, but does cause a substantial module replacement-cost contribution. This cost also varies with the number of series blocks because of improvements in module manufacturing yield that occur when module series-paralleling achieves high levels.

The key conclusion drawn from Figure 14 is that the optimal maintenance strategy is not to replace modules for routine sporadic cell failures, but instead to absorb the small economic penalty associated with corresponding gradual decrease in plant power output.

The analysis was repeated for various sizes of modules and system voltage levels to define optimum circuit configuration, module size, and replacement strategy for each system type (see References 80 and 82).

F. ELECTRICAL COMPONENTS

Although a PV module primarily is composed of solar cells and encapsulants, two additional electrical components with important functions and cost contributions are bypass diodes and electrical terminations (junction boxes and/or connectors). Reliability and cost issues related to module electrical terminations led to early JPL studies of off-the-shelf candidates (Reference 83), and subsequently to a contract with Motorola and Cannon to define alternatives (Reference 84). Through the years, collaborative work with Amp, Inc. has led to a complete family of low-cost termination products especially designed for PV applications (Figure 15).

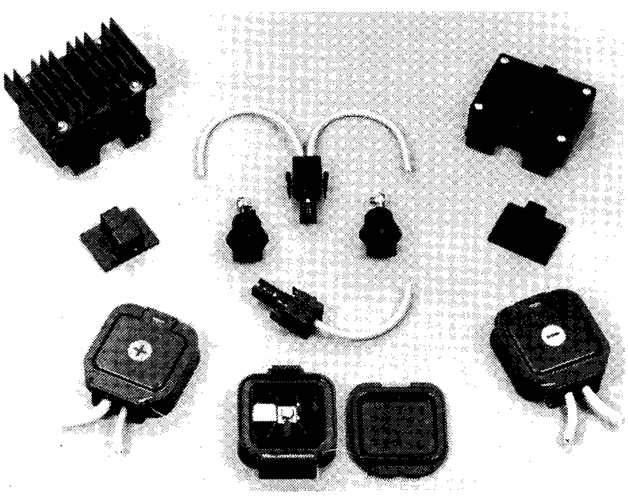


Figure 15. Low-Cost Connectors Developed for PV Applications

In circuit analysis and hot-spot heating studies conducted by JPL, strong evidence was generated for use of bypass diodes in array applications. Because periodic estimates of the cost of bypass diodes ranged as high as $0.50/W$_p$ of array capacity, GE received a contract to develop improved cost estimates and to develop low-cost mounting approaches for integrating the diodes into modules and arrays (References 85 through 88). Large-capacity bypass diodes, such as the dual 60 A diode (Figure 16), have been shown to cost about $0.03/W$_p$ of array capacity. One of the pictured units is used for each 1 kW panel in the first 1 MW plant of the Sacramento Municipal Utility District (SMUD).

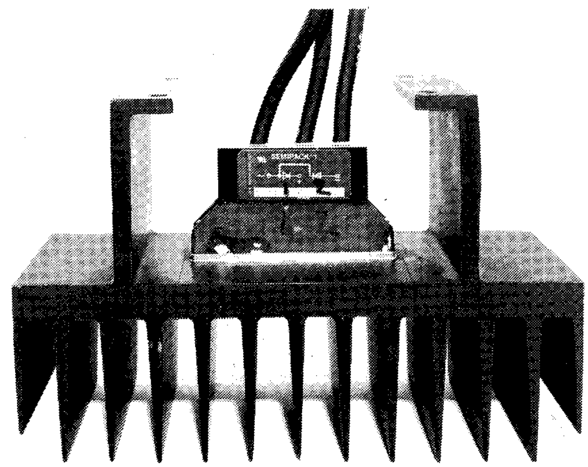


Figure 16. Dual 60-A Bypass Diode Used in SMUD PV Power Plant

G. ARRAY-LOAD INTERFACE CHARACTERIZATION

To control I^2R power losses in power-conversion equipment, or to otherwise satisfy the load, an array generally is required to provide maximum power at a specified voltage level. Small systems (up to a few hundred watts) generally require 12 to 24 V, residential and intermediate load-center systems (from 5 to 100 kW) generally require 100 to 300 V, and large megawatt-level installations require a maximum of 1000 V.

An important consideration in the design of the array-load interface is that the array current is proportional to the instantaneous irradiance level, and the array voltage decreases about 0.5% per 1 °C of increasing solar-cell temperature. The array load, therefore, must accommodate substantial current and voltage variations caused by changing ambient conditions while continuously maximizing the power received from the array.

To assist the designers of power-conversion equipment, JPL conducted an extensive study of array-load interface design considerations including quantification of the pros and cons of various load-control strategies and estimation of maximum expected array voltage and current levels (References 89 and 90). The results were generated parametrically in a manner useful for any array size, voltage level, or geographic location.

H. SIGNIFICANT ACCOMPLISHMENTS

Specific technology developments that evolved from the engineering research activity include:

(1) Low-cost ground-mounted array-design approaches including frameless modules.

(2) Roof-mounted array design approaches.

(3) Wind pressure loads on flat modules and arrays including dynamic flutter loads.

(4) Data on array cleaning costs and automated washing techniques.

(5) Guidelines for optimum maintenance/replacement of failed modules in the field.

(6) Module and array thermal-design guidelines for cooler operation, resulting in increased power output and longer life.

(7) Standardized module thermal testing methods.

(8) Module electrical insulation system-design guidelines and testing techniques.

(9) Fire-resistant module designs and encapsulant materials.

(10) Array series/parallel electrical circuit-design guidelines including grounding and bypass-diode design guidelines.

(11) Module electrical terminal needs and designs.

(12) Bypass-diode packaging and mounting approaches.

(13) Design guidelines for optimally interfacing arrays with power conditioners.

SECTION IV

Reliability Technology Development

A. BACKGROUND

Another key objective of the Engineering Science and Reliability Area of the FSA Project, together with the Encapsulation Task, was to guide and develop the technology base required to achieve modules with 30-year lives. At the beginning of the Project in the early 1970s, typical terrestrial modules were either very expensive, or had lifetimes ranging from 6 months to 2 to 3 years. As a result of site visits to early commercial applications and experience with the first block procurements, it became clear that substantial research was needed to provide the technology required to achieve 20- to 30-year life modules.

The reliability issues of the early PV industry were not unique to its technology, but stemmed from the general lack of technology enabling prediction of the complex chemical and physical reactions involved in long-term aging. Unlike more complex systems, however, PV modules had the advantage of a very limited number of different types of components. This allowed a high level of research and testing to be focused on each failure mechanism. Conversely, in the classical case of having all of your eggs in one basket, if there is a generic problem with a component of a PV module, a large fraction of the PV system is at risk. This also demanded that PV failure mechanisms be well understood and solved.

During the course of the Project, a steady stream of module failure mechanisms (shown in Figure 17) was observed and identified through module testing, application experiments, and failure analyses (see References 8 and 9). To resolve the reliability problems, a systematic research effort was undertaken (References 12, 14, 15, and 91) with parallel efforts focused on the most troublesome failure mechanisms (Figure 18). In carrying out the research, the engineering area of the Project emphasized mechanisms associated with the solar cells, the module structure, and the electrical circuit and safety, while the Encapsulation Task emphasized issues dealing with polymer encapsulants.

An important initial focus of the engineering research was the development of test methods useful for quantifying reliability weaknesses during the module design phase. This led to the early definition, development, and extensive refining of module qualification tests to catch known design deficiencies, while passing modules with good in-the-field performance (see References 4, 5, and 42). As progress was made, emphasis continually was refocused toward achieving a physical understanding of the less-well-understood failure mechanisms and to devising design solutions for them.

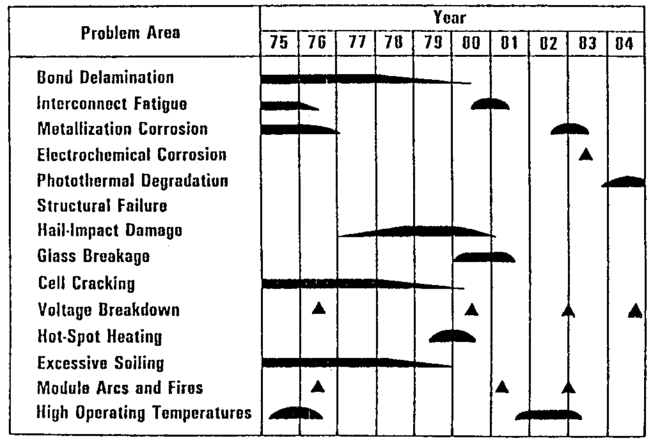


Figure 17. Periods of Occurrence of Significant Field Failures in Various Mechanism Categories

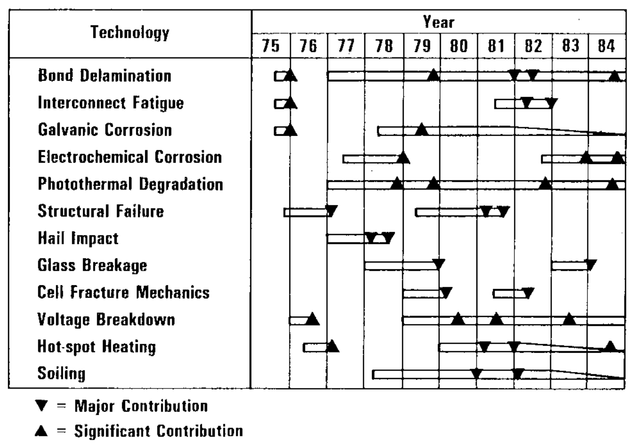


Figure 18. Reliability and Durability Developments, 1974 to 1984

During the course of the Project, reliability research evolved into a general methodology with six major elements:

(1) Identification of key degradation and failure mechanisms.

(2) Establishment of mechanism-specific reliability goals.

(3) Quantification of mechanism parameter dependencies.

(4) Development of degradation prediction methods and qualification tests.

(5) Identification of cost-effective solutions.

B. RELIABILITY MANAGEMENT

In carrying out the above research, the first two elements evolved naturally into an overall reliability management function, and the third through the fifth elements were implemented as separate integrated activities for each failure mechanism. This approach allowed specialist teams to address individual mechanisms while the management activity scoped the problem as a whole, established priorities for mechanism-level research within budget constraints, and provided specific reliability goals for each mechanism.

1. Identification of Failure Mechanisms

An important reliability management activity was to ensure that all important failure and degradation mechanisms were identified and that significant resources were not expended on less important problems. A key criterion in this regard was the extent to which a failure mechanism was generic to a majority of state-of-the-art module designs as opposed to being associated with a single module or manufacturing process. Inclusion of a wide variety of test modules from various manufacturers allowed this separation and helped ensure the broad applicability of analysis and test methods developed and solutions identified.

The most important indicator of failure mechanism importance was found to be well documented field failures (see Reference 42). This required careful monitoring of field applications with statistically significant numbers of modules, and an active problem-failure reporting system. Detailed failure analysis to identify fundamental failure mechanisms was a critical step.

Qualification testing also highlighted large numbers of failures, but this evidence was much less convincing because of the small number of samples in test and the lack of quantitative correlation to field performance. Similarly, good performance in non-operating field test racks, as contrasted to performance in operating PV systems, was found to be a necessary, but not sufficient condition for long life. In effect, system interface stresses such as applied voltages and currents play a significant role in PV failure mechanisms. Hot-spot heating failures, shorts to ground, and in-circuit arcs are important examples of failures that required operating systems for quantification.

Unfortunately, none of the failure-identification techniques discussed above was found effective in identifying long-term failure mechanisms that only show up after prolonged field exposure. The study of these mechanisms required the development of intermediate length (6-month to 2-year) life tests that included relevant stresses and achieved acceleration levels of 10 to 50.

Experience during the Project has shown that increased temperature is the most reliable accelerator for a variety of mechanisms. Increased humidity, applied voltage, and accentuated stress cycling also were found to be useful accelerators. Cell testing at Clemson University, module testing at Wyle Laboratories, and encapsulant testing at Springborn Laboratories are examples of key research activities addressed to identifying important long-term mechanisms (References 32, and 92 through 94).

2. Establishment of Mechanism-Specific Reliability Goals

Once key failure-mechanisms were identified, an important next step in the management process was to establish target degradation allocations for each mechanism, consistent with the overall goal (Figure 19) of 20- to 30-year module life. A critical step in this process was quantification of the economic importance at the system level of each failure or degradation occurrence. For some mechanisms, such as encapsulant soiling, the economic impact is directly proportional to the degradation level and is easily calculated. For others, such as open-circuit or short-circuit failures of individual solar cells, elaborate statistical-economic analyses that included effects of circuit redundancy, maintenance practices, and life-cycle costing were required (see References 12, 82, and 91). Development of these analytical tools was described in Section III of this report.

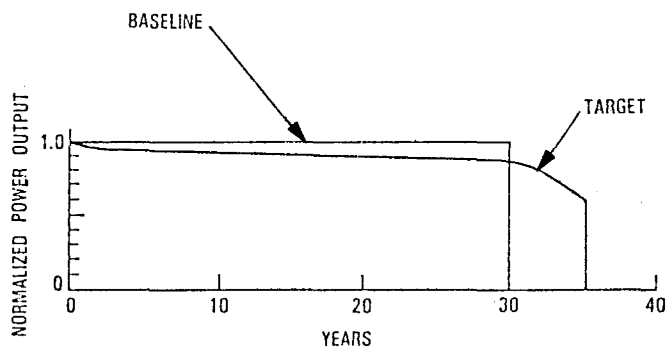


Figure 19. Typical Target Allocation for Time-Dependent Power Degradation

Table 6 lists 13 principal failure mechanisms identified for flat-plate crystalline-silicon PV modules, together with their economic significances and target-allocation levels (see Reference 14). The units of degradation, listed in the third column, provide convenient means to quantify the failure levels of individual mechanisms according to their estimated time to failure. For example, units of percent per year in the context of component or module failures reflect a constant percentage of components failing each year. For components that fail with increasing rapidity, percent per year per year (%/y^2) is the unit used to indicate linearly increasing failure rate. This failure trend is most easily interpreted by noting that the failure rate after (A) years is (A) times the %/y^2 value. For those

Table 6. System Life-Cycle Energy Cost Impact and Allowable Degradation Levels for Flat-Plate Crystalline Silicon Modules

Type of Degradation	Failure Mechanism	Units of Degrad.	Level for 10% Energy Cost Increase*		Allocation for 30-year Life Module	Economic Penalty
			k = 0	k = 10		
Component failures	Open-circuit cracked cells	%/yr	0.08	0.13	0.005	Energy
	Short-circuit cells	%/yr	0.24	0.40	0.050	Energy
	Interconnect open circuits	$\%/yr^2$	0.05	0.25	0.001	Energy
Power degradation	Cell gradual power loss	%/yr	0.67	1.15	0.20	Energy
	Module optical degradation	%/yr	0.67	1.15	0.20	Energy
	Front surface soiling	%	10	10	3	Energy
Module failures	Module glass breakage	%/yr	0.33	1.18	0.1	O&M
	Module open circuits	%/yr	0.33	1.18	0.1	O&M
	Module hot-spot failures	%/yr	0.33	1.18	0.1	O&M
	By-pass diode failures	%/yr	0.70	2.40	0.05	O&M
	Module shorts to ground	$\%/yr^2$	0.022	0.122	0.01	O&M
	Module delamination	$\%/yr^2$	0.022	0.122	0.01	O&M
Life-limiting wearout	Encapsulant failure due to loss of stabilizers	Years of life	27	20	35	End of life

*k = Discount rate

mechanisms classified under power degradation, the percent per year units refer to percentage of power reduction each year.

Using the units described above, columns 4 and 5 of Table 6 indicate the level of degradation for each mechanism that will result in a 10% increase in the cost of delivered energy from a large PV system. Because the mechanisms generally will occur concurrently, the total cost impact is the sum of the 13 cost contributions. Column 6 lists the strawman allocation of allowable degradation among the 13 mechanisms to achieve a total reliability performance consistent with expectations of a 30-year life. The total effect of the allowable levels is a 20% increase in the cost of energy compared to that from a perfect, failure-free system.

C. RELIABILITY PHYSICS INVESTIGATIONS

Once a key failure mechanism was identified and quantitative goals were established for field-failure levels, the challenge was to achieve the levels and know that they had been achieved. This very difficult phase can be described as containing three research elements: quantification of parameter dependencies, development of degradation prediction methods, and identification of cost-effective solutions. These research elements were integrated into the study of each failure mechanism and were the focus of the research team addressing each mechanism. Thus, once mechanism-specific reliability goals were established, research activity was divided up on a failure mechanism basis, with each mechanism-specific team responsible for understanding the mechanism, developing predictive test and analysis methods (including qualification tests), and investigating design solutions.

A key thrust of each mechanism-specific research effort was to attempt to quantify the chemical and physical processes involved in the degradation. Although only a qualitative insight into the mechanism physics was normally achieved, the improved level of understanding generally was invaluable in identification of principal degradation parameters and qualitatively understanding their influence. Heavy emphasis was placed on empirical characterization of failure rates based on least squares fitting a general mathematical function through a large quantity of empirical test data gathered at parametric stress levels. This technique of using carefully selected mathematical functions to unify and interpolate among parametric test data was found to be an excellent way to quantify mechanism-parameter dependencies. Knowledge of the mechanism physics played a key role in selecting the experimental parameter to be measured and in choosing the form of the mathematical functions to be fit to the data.

Once parameter dependencies were characterized, the problem of life-prediction required understanding the time-history of applied stresses associated with the subject exposure, be it 30 years of field weathering or 6 months in an accelerated test environment. Substantial skill generally was necessary to achieve an adequately accurate prediction with available resources.

During the course of the Project, a variety of environmental stress characterizations were developed. These include models of hail-impact probability (see Reference 26), wind loading pressures (see Reference 59), and array voltage and current durations. In addition, SOLMET weather-data tapes (see References 30 and 31) were used extensively to model UV, temperature, and humidity exposure levels of modules (see References 32 and 33). These models often were combined with complex, degradation parameter dependencies to achieve useful life-predictions for various failure mechanisms (see Reference 33).

As a normal part of each mechanism-specific research activity, various design approaches and materials were included in the parametric testing and life-prediction analyses. As a result, these activities also served to identify viable solution concepts and provide the tools to compute their cost-effectiveness. The latter required trade-offs of degradation rates, failure rates, and life against initial manufacturing costs, field-maintenance costs, and lost energy revenues. Life-cycle costing served as an excellent mathematical tool to integrate these disparate economic terms and to allow cost-effectiveness to be quantified and trade-offs to be made (References 82 and 95). Models for predicting the economic impact of individual failures upon the system were used here, as they also were in establishing the quantitative reliability goals described earlier. A necessary part of defining cost-effective solutions was to reconcile and iterate initial goals with the realities of available technologies used in the most cost-optimum manner. When available technologies fell short, they were highlighted for continued research.

The following paragraphs highlight the key reliability-physics investigations carried out during the course of the Project. These include research on:

(1) Interconnect fatigue.

(2) Optical surface soiling.

(3) Hail-impact resistance.

(4) Glass-fracture strength.

(5) Cell-fracture strength.

(6) Cell reliability.

(7) Long-term temperature-humidity endurance of modules.

(8) Hot-spot heating.

(9) Bypass-diode reliability.

(10) Electrical breakdown of insulation systems.

(11) Electrochemical corrosion.

1. Interconnect Fatigue

Individual solar cells of a module generally are interconnected in series by metallic ribbon conductors that lead from the bottom of each cell to the top of the next, as shown in Figure 20. The large number of series cells in a high voltage (>100 V) array makes an array very sensitive to open-circuits caused by either cell failures or failure of the interconnects that connect adjacent cells (see Reference 14). Achieving high reliability requires cell and interconnect failures to be held to low levels and that fault-tolerant circuit redundancy be optimally used.

During the course of the Project, extensive research was conducted on interconnect failure caused by mechanical fatigue (Figure 21). This is a classical failure mechanism that has been prevalent in spacecraft arrays as well as terrestrial arrays. It primarily is caused by ther-

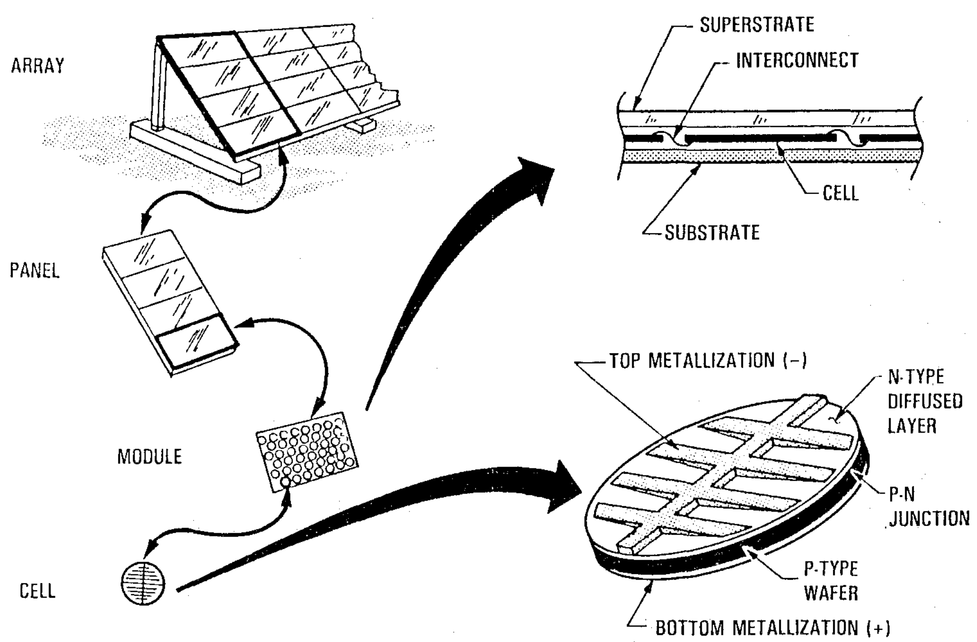


Figure 20. Photovoltaic Nomenclature

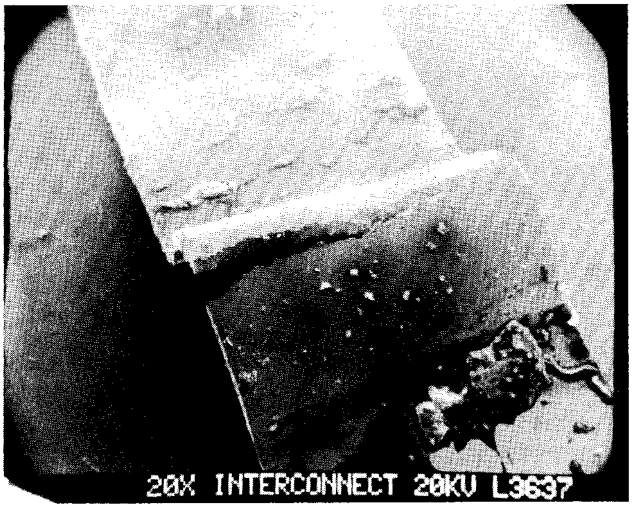


Figure 21. Scanning Electron Microscope Image of Fatigued Interconnect

mal and humidity expansion differences between the cell and its supporting substrate or superstrate.

Mon, Moore, and Ross (References 96 through 98) empirically characterized the fatigue-failure statistics of a variety of both interconnect materials and geometries, and published detailed design methods for achieving optimal levels of interconnect reliability. From empirical data, interconnects were found to fail with a log-normal distribution, with the weakest failure occurring as much as 100 times sooner than the average. Figure 22 presents example fatigue curves that quantify the probabilistic nature of the failure of copper interconnects. Because of statistical variability, the use of multiple interconnects was found useful in preventing open circuits caused by failure of the interconnects or their attachments to the cells. Methods also were derived that allow users to select optimal levels of interconnect redundancy based on minimizing life-cycle energy costs of an array (see References 96 through 98).

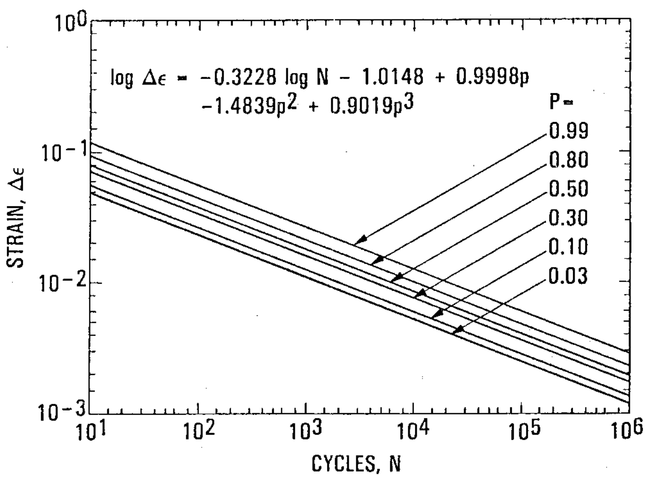


Figure 22. Fatigue Curves for OFHC 1/4-Hard Copper Versus Failure Probability (p)

Figure 23 presents the life-cycle energy cost (as a percentage of total PV system cost) for a variety of solar cell interconnect materials as a function of interconnect thickness (see Reference 97). The plotted costs include manufacturing costs, efficiency losses because of solar cell shading and I^2R losses, and power degradation because of interconnect fatigue failures. The latter are responsible for the rapidly rising trend on the right side of each cost curve. Such an analysis allowed quantitative judgments to be made and cost-effective levels of reliability to be selected.

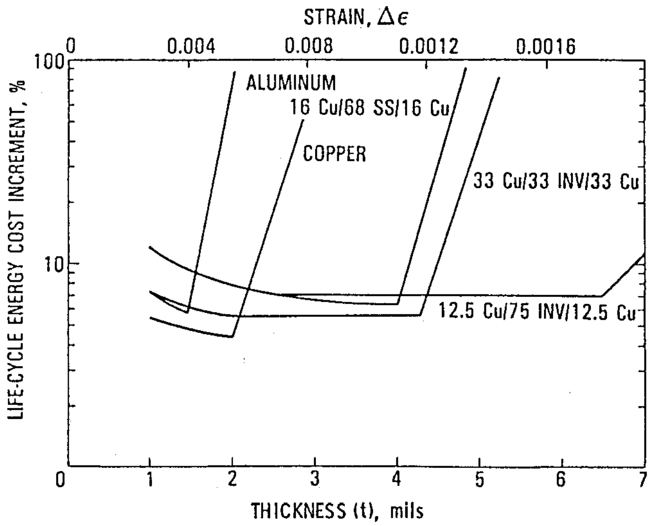


Figure 23. Life-Cycle Cost Contribution of Doubly Redundant Interconnects as a Function of Material Thickness (1 mil = .0254 mm)

2. Optical Surface Soiling

Loss of module power because of soiling of the front surface encapsulant was a critical problem with early silicone-rubber modules of the mid 1970s (Reference 99). As a result, an extensive test program was conducted at a variety of site locations throughout the United States to characterize the nature and level of soiling with various encapsulants (Reference 100).

Although similar in effect to other optical-loss mechanisms, the experimental data indicated that optical surface soiling caused by dust and atmospheric contaminants reached equilibrium levels in a few weeks and then fluctuated somewhat with natural cleaning mechanisms such as rain. Figure 24 illustrates this soiling behavior for a variety of module surface materials in two site environments: one urban, the other remote. The severe soiling behavior of a typical unprotected silicone rubber is clearly visible.

Although the data indicate that, without washing, average soiling levels below 5% should be easily achievable with glass or Tedlar-like optical-surface materials, it also was observed that the effect of soiling is greater at non-normal angles of incidence. A study subsequently was conducted that characterized the angular dependence of module electrical efficiency

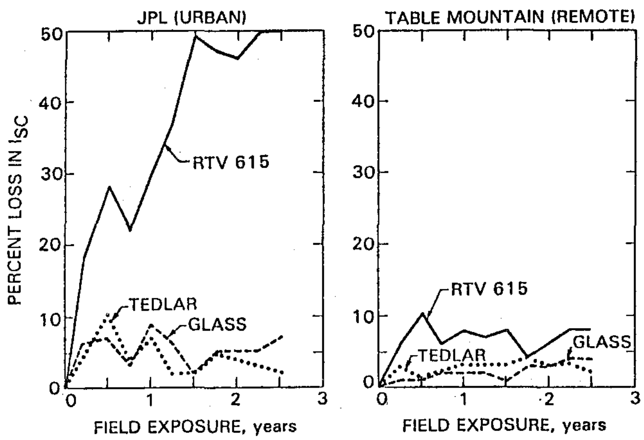


Figure 24. Loss in Array Short-Circuit Current (I_{SC}) Because of Soiling Versus Years of Field Exposure

(with and without soiling) on off-normal irradiance, and developed analytical models for use in energy performance calculations (Reference 101).

Research attempts also were made to develop a laboratory soiling-resistance test (see References 4 and 100). These were only marginally successful because of the complex soiling and cleaning processes in the natural environment. Because the soiling behavior becomes apparent quickly in the field, natural outdoor soiling tests were adopted as the most reliable means of characterizing the self-cleaning properties of front-surface encapsulants. Based on empirical soiling data, general theories of soiling were hypothesized and anti-soiling coatings were developed within the Project's Encapsulation activity (Reference 102).

3. Hail-Impact Resistance

Another source of early module failures was impact by hailstones. In the 1976 to 1978 time frame, extensive research was conducted to develop means of testing hail-impact resistance of various module constructions and to define cost-effective protection approaches and levels (Figure 25). As an excellent example of the integrated nature of the reliability-physics efforts, research developed the hail-impact gun shown in Figure 25, defined the qualification test noted in Table 1, and provided definitive design guidance for achieving the required levels of protection (References 103 and 104). The final Block V requirement for resistance to 1-in.-diameter hailstones is based on field experience that indicated this level of protection is necessary to achieve acceptably low probabilities of failure, even in low hail-incidence regions of the country.

4. Glass-Fracture Strength

During the first central-station array-design study conducted by Bechtel Corp., it was discovered there were neither readily available methods for determining the stress in glass associated with uniform wind pressure loads, nor were there reliable data on the strength of glass. Typical linear theory for stress versus load led to unrealisticly thick glass, thus ruling out large 4 x 8 ft PV modules. The principal problem was thin glass sheets undergo large out-of-plane deflections that make linear stress-deflection relationships in error by as much as a factor of two. The fracture strength of glass also is a complex, poorly-documented function of such things as glass area, time of loading, flaw-distribution statistics, and residual stress (temper).

In 1978, JPL and Bechtel (see Reference 19) conducted detailed investigations of stress distribution in glass using non-linear finite-element structural-analysis computer codes. These investigations were successful in understanding the stress in glass during large out-of-plane deflections and set the stage for close collaboration with the community of glass researchers. As one solution to reducing glass support requirements, Bechtel Corp. studied the concept of a curved glass module (see Reference 75).

JPL researchers collaborated with glass researchers at Texas Tech University, Pittsburgh Plate Glass Corp., and Libby Owens Ford, and developed definitive stress-prediction algorithms and glass-strength data (Reference 105). Non-linear finite-element computer codes were used to develop generic non-dimensional solutions for stress versus loading level (Figure 26) and more than 2000 individual breaking-strength data were used to characterize accurately the breaking probability of glass as a function of maximum tensile stress, plate area, time of loading, and temper (Figure 27) (Reference 106).

5. Cell Fracture Strength

Breaking of thin, crystalline-silicon solar cells was another problem prevalent in early PV modules. To better understand the parameters that determined the breaking strength of silicon solar cells, a novel test method was developed and an extensive test program was conducted. Definitive data, as shown in Figure 28, provided an extensive characterization of the effect of various cell-processing steps on the fracture probability of crystalline-silicon wafers (References 107 through 109).

6. Cell-Reliability Investigations

Crystalline-silicon solar cells sometimes exhibit reliability problems related to increased series resistance, junction shunting, and deterioration of the cell antireflective (AR) coating. Increased series resistance often is associated with a gradual deterioration of adherence between the cell metallization and the cell bulk material caused by corrosion-related processes, or the deterioration of the ohmic contact through the formation of a Schottky barrier. Junction shunting, which is much less common, may be caused by diffusion or migration of metallization elements into the cell junction or over the external surfaces of the cell. The third cell-degradation mechanism relates to the deterioration of the AR coating on the solar cell's irradiated

HAIL IMPACT RESEARCH

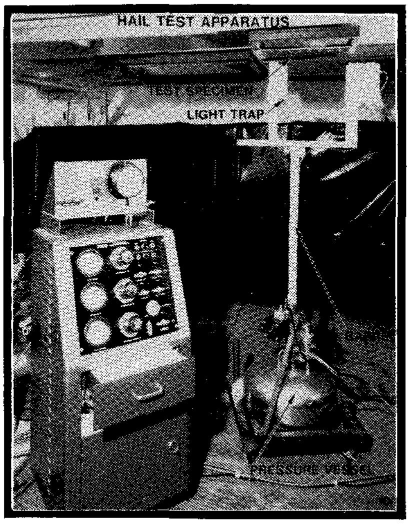
OBJECTIVES

- DEVELOP HAIL TEST APPARATUS AND PROCEDURE AND CONDUCT RESEARCH ON MODULE FAILURE MECHANISMS CAUSED BY HAIL IMPACT
- DEVELOP STATISTICAL DATA DEFINING PROBABILITY OF IMPACT BY VARIOUS HAIL SIZES IN GEOGRAPHIC REGIONS OF UNITED STATES
- CONDUCT MODULE HAIL RESISTANCE COST/BENEFIT ASSESSMENT

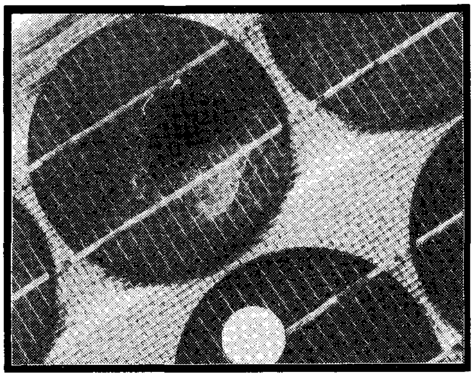
SUSCEPTIBLE PARTS

- CELLS (ESPECIALLY EDGES NEAR ELECTRICAL CONTACTS)

  ENCAPSULANT SYSTEM (CORNERS AND EDGES, POINTS OF SUPERSTRATE SUPPORT, POINTS OF MAXIMUM DISTANCE FROM SUPERSTRATE SUPPORT)



EXPERIMENTAL HAIL RESISTANCE TEST APPARATUS



HAIL IMPACT DAMAGE ON DEVELOPMENTAL MODULE (3/4-in. ICE BALL)

HAIL IMPACT RESISTANCE

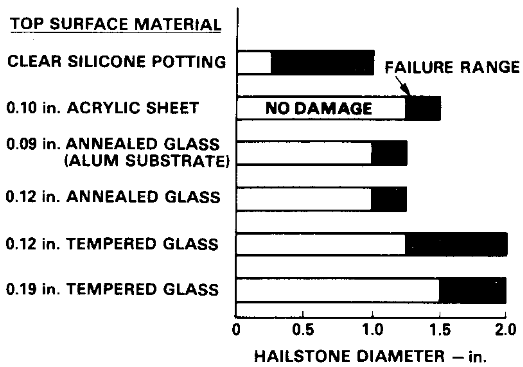


Figure 25. Hail-Impact Test Development and Data

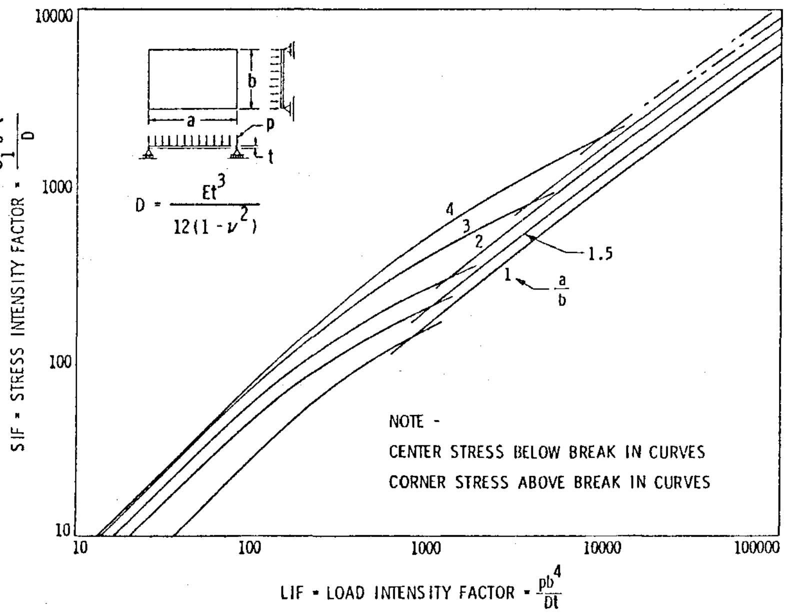


Figure 26. Glass Stress Curves: Maximum Principal Stress Versus Load

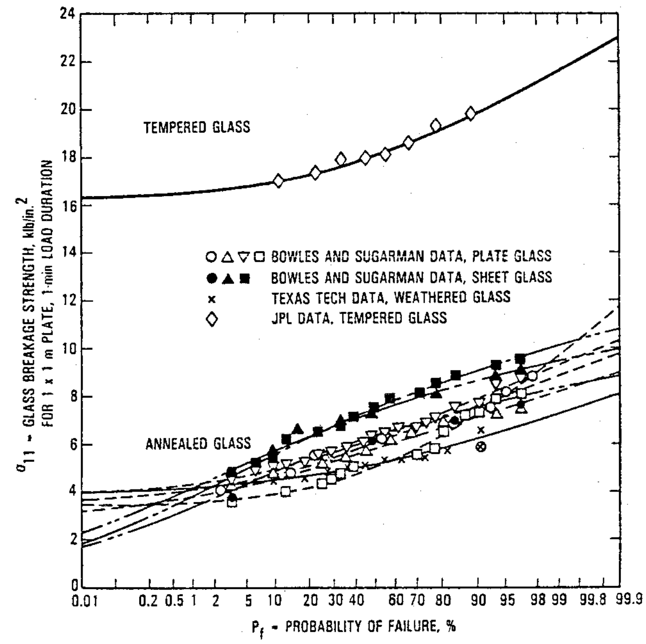


Figure 27. Maximum Stress Level (σ_{11}) Required to Break a Given Percentage of Identical Glass Plates

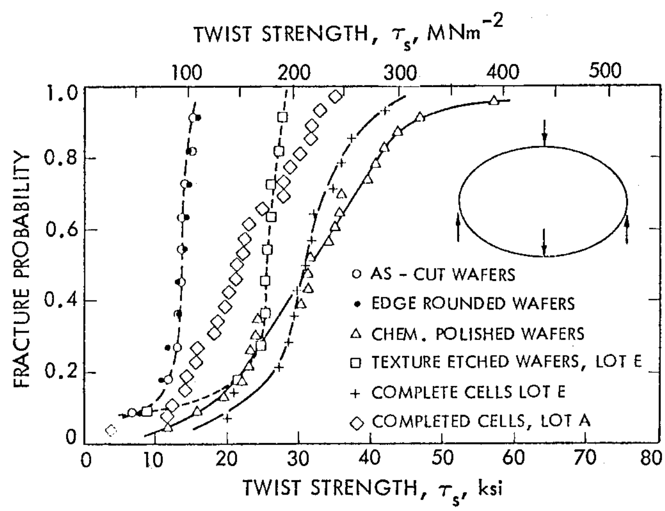


Figure 28. Effect of Cell Processes on the Fracture Strength of Silicon Wafers and Cells

surface because of leaching or contamination from plating or corrosion products. All of these mechanisms lead to a gradual reduction in a cell's electrical efficiency and are quite sensitive to the choice of metallization and AR coating materials and processes.

In 1976, JPL initiated a contract with Clemson University to conduct an investigation and characterization of the reliability attributes of a broad cross-section of available commercial and research solar cells. Between 1976 and 1986, Clemson personnel tested hundreds of solar cells from most of the leading cell manufacturers and developed definitive methods for cell-reliability testing. Their work shows that moisture and thermal aging are key environmental stresses, and that the module encapsulant system exacerbates the problem as often as it helps (References 92 and 110).

In all three mechanisms, the most effective techniques identified for quantification of expected levels of degradation involve accelerated temperature/humidity testing together with Arrhenius plotting and other means of relating the data to long-term use conditions.

7. Long-Term Module Temperature-Humidity Endurance

Complementing the Clemson University research on cells, long-term temperature-humidity testing of complete modules was conducted by JPL personnel using the facilities of Wyle Laboratories in Huntsville, Alabama. This test program focused on the synergistic reactions between cells and the module encapsulant system and highlighted problems such as electrochemical corrosion of cell metallization, chemical contamination from edge seals and gaskets, and catalysis of encapsulant yellowing by cell and bus bar metallic ions. Research results provided definitive estimates of the expected reliability of several module construction types that used leading encapsulants and cell-metallization systems (see References 32 and 93).

8. Hot-Spot Heating

A unique failure mechanism associated with solar cells is excessive local hot-spot heating that can occur when a cell or group of cells is subjected to a current level greater than the cell's short-circuit current. As shown in Figure 29, this condition can be caused by a variety of circuit faults such as cell cracking, local shadowing, and open-circuiting of series/parallel connections. When the degree of heating exceeds safe levels (100 to 120°C in most modules), the module's encapsulant system can suffer severe permanent damage (Figure 30). Preventing such damage requires the use of bypass diodes or other corrective measures to limit the maximum heating level. Many investigations have led to a definitive understanding of the phenomena, means of determining the number of bypass diodes required, and test methods to verify that hot-spot heating is limited to safe levels (References 111 through 113). For most cells and module constructions, a bypass diode is required about every 10 to 15 series cells.

9. Bypass Diode Reliability

Bypass diodes, as shown in Figure 31, are an important means of improving array reliability. At the same time, they introduce additional failure mechanisms including diode shorting under conditions of excessive junction temperature, and diode shorts to ground because of inadequate electrical isolation from

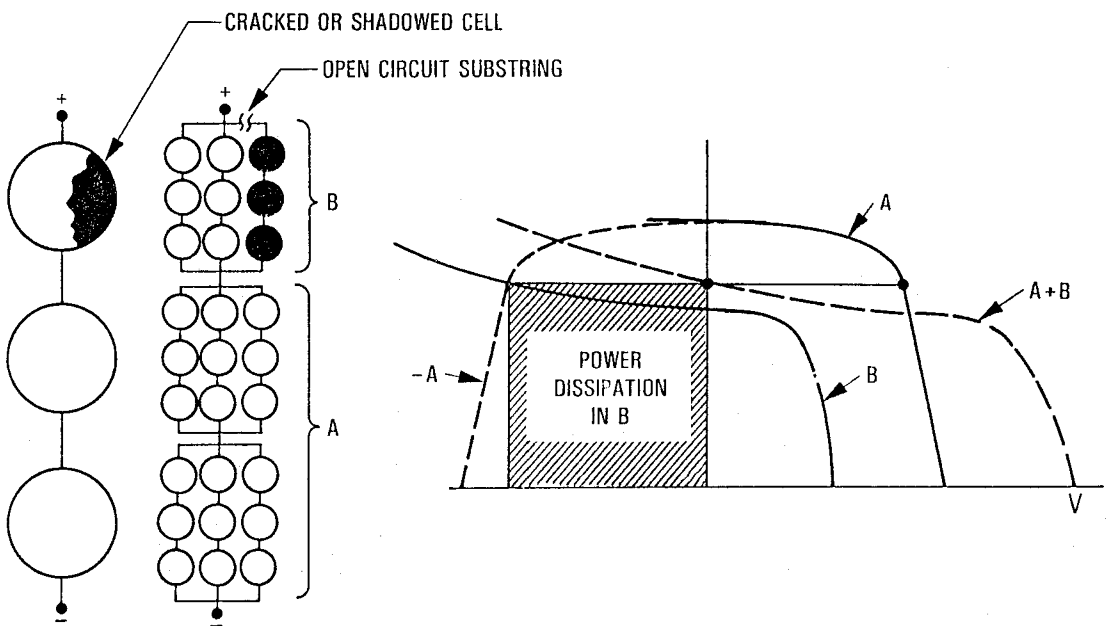


Figure 29. Visualization of Hot-Spot Cell Heating

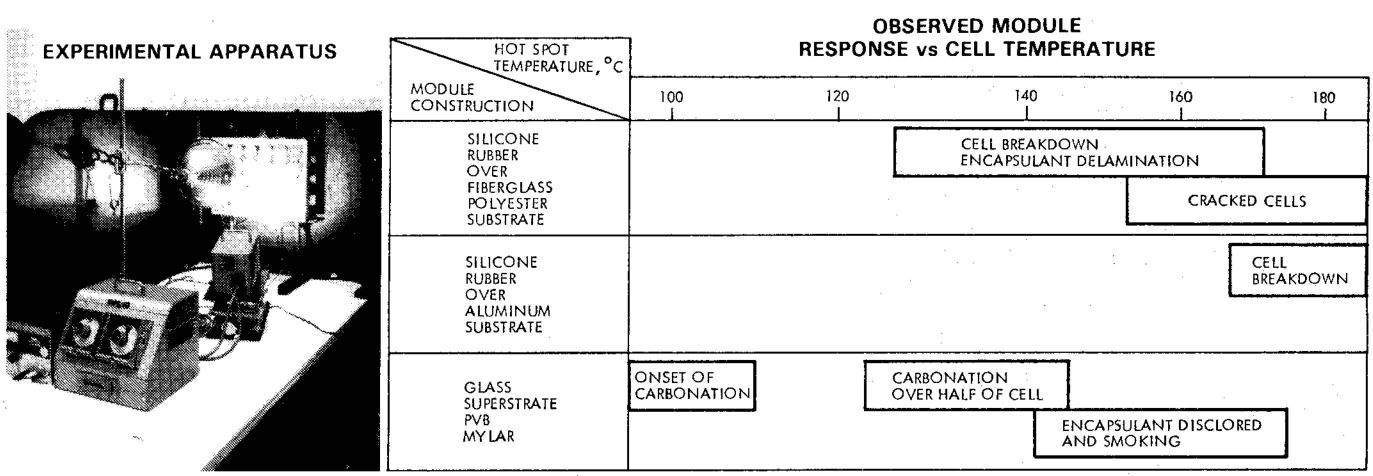


Figure 30. Hot-Spot Endurance Test Development

grounded heat-sink assemblies. Work carried out at GE (see Reference 88), as part of its bypass-diode packaging study, indicates that very little historical reliability data are applicable to the PV module-bypass application, which involves long periods of low reverse voltage (5 V) together with periodic high forward currents. Because diode junction temperature is the critical factor related to long-term reliability, JPL developed detailed test procedures for measuring junction temperature in situ under simulated worst-case field conditions, and defined guidelines recommending that the junction temperature of silicon diodes be maintained below 125°C under conditions of maximum bypass current and ambient temperature (Reference 114).

10. Electrical Breakdown of Insulation Systems

From a safety point of view, an important module failure-mechanism is breakdown of the electrical insulation system between the cell circuit and grounded module exterior surfaces. The maximum voltage stress includes consideration of maximum open-circuit array voltages achieved under low temperature (0°C) and high irradiance (100 mW/cm^2), as well as transient overvoltages, for example, because of system feedback of lightning transients. The latter is bounded by the characteristics of incorporated voltage-limiting devices such as metal-oxide varistors (MOVs).

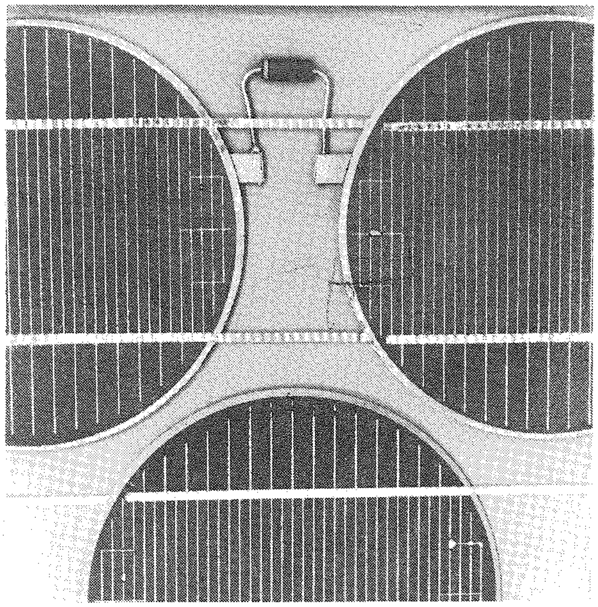
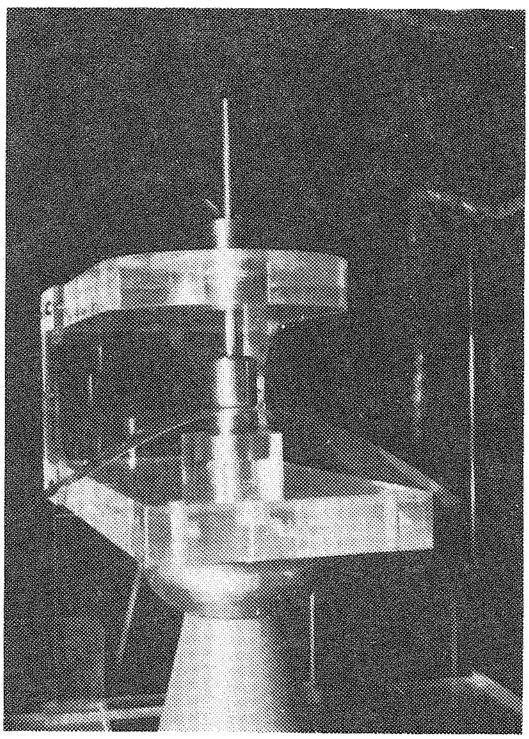


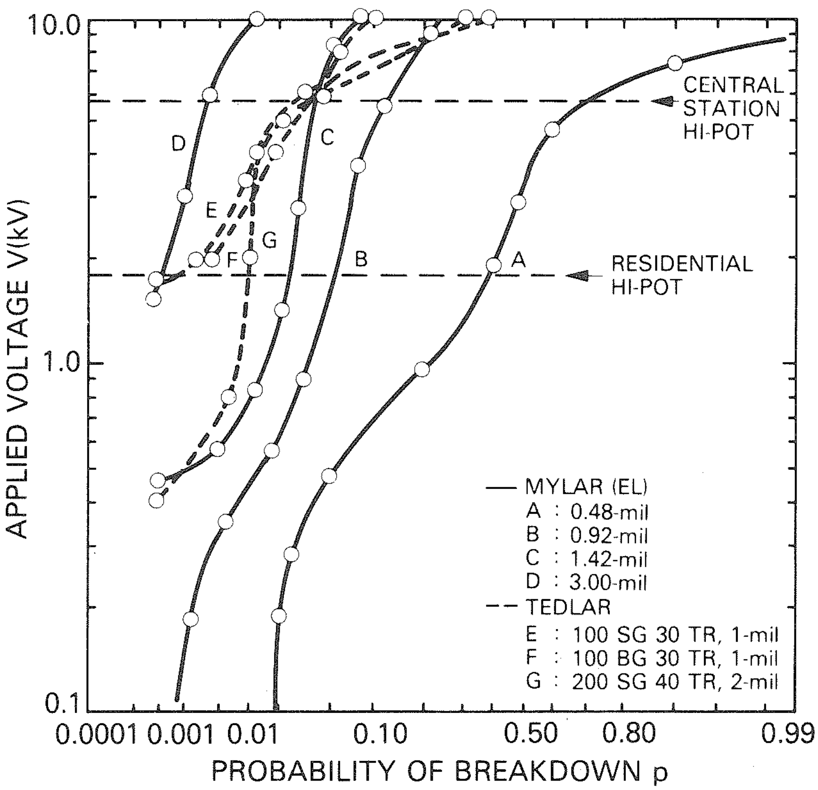
Figure 31. Typical Bypass-Diode Installation Integral to a PV Module

Early interest in voltage-withstand criteria for high-voltage central-station applications led to a first exploratory study of insulation design practices for PV modules by Bechtel Corp. in 1978 (see Reference 75). The work pointed up a major deficiency in our understanding of the breakdown phenomena in general, and highlighted a lack of available insulation design methods, specifically for long-term direct-current applications involving outdoor weathering of insulation materials.

Research was conducted on various aspects of this problem and has led to extensive characterization of insulation flaws present in films of Mylar and Tedlar (Figure 32), and of the field-stress enhancement that occurs in the vicinity of sharp edges of conductors (References 115 and 116). Other work on the voltage-withstand ability of encapsulants led to improved understanding of the intrinsic breakdown-strength of polymers (References 117 and 118). Work on electrochemical corrosion led to leakage-current studies that developed a definitive understanding of the role of moisture in the determination of ionic conduction properties of module encapsulants and in the quantification of the relative roles of surface, bulk, and interface conduction (References 119 through 121).



HIGH VOLTAGE THIN FILM INSULATION BREAKDOWN RESEARCH APPARTUS



THIN FILM TEST BREAKDOWN DATA

Figure 32. Insulation Breakdown Research

11. Electrochemical Corrosion

Electrochemical corrosion of solar cell metallizations first was observed in long-term tests of modules under accelerated temperature-humidity conditions at Wyle Laboratories. Corrosion is caused by leakage currents associated with migration of metallic ions between module components operating at different voltage levels. Of most concern, as shown in Figure 33, is the transport of cell metallization between adjacent cells and between the cells and the grounded module frame. With time, cell performance is destroyed and corrosion products, such as the dendrites shown in Figure 34, may bridge the insulation with a conductive path that results in a short to the grounded module frame.

Research conducted during the Project quantified the relationship between charge transfer and cell-performance degradation (Figure 35) and developed a definitive understanding of the role of encapsulants, moisture, and temperature in establishing corrosion rates (References 119 through 124).

D. SIGNIFICANT ACCOMPLISHMENTS

Key accomplishments, resulting from reliability-research activities, included the following:

(1) Developed definitive allocations for the reliability required for each module failure-mechanism and defined the economic impact of each failure.

(2) Developed analytical tools and design data for both the prediction of interconnect fatigue and the design of long-life, reliable cell interconnections.

(3) Developed long-term soiling data for various module surface materials.

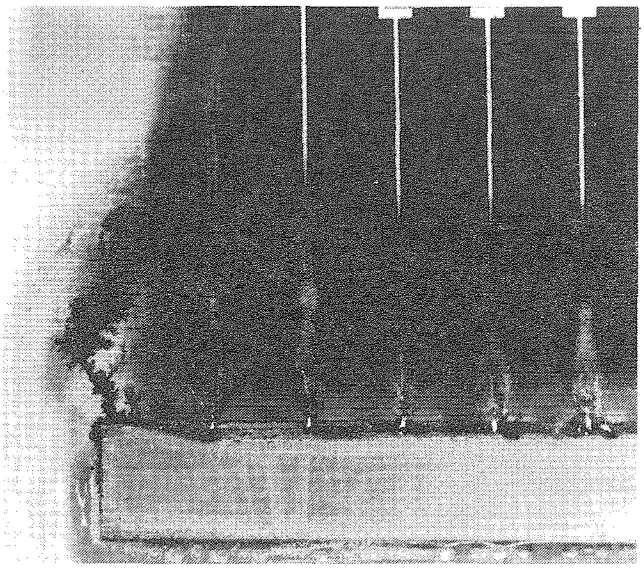


Figure 34. Dendritic Growth from Electrochemical Corrosion of Solar Cell Metallization

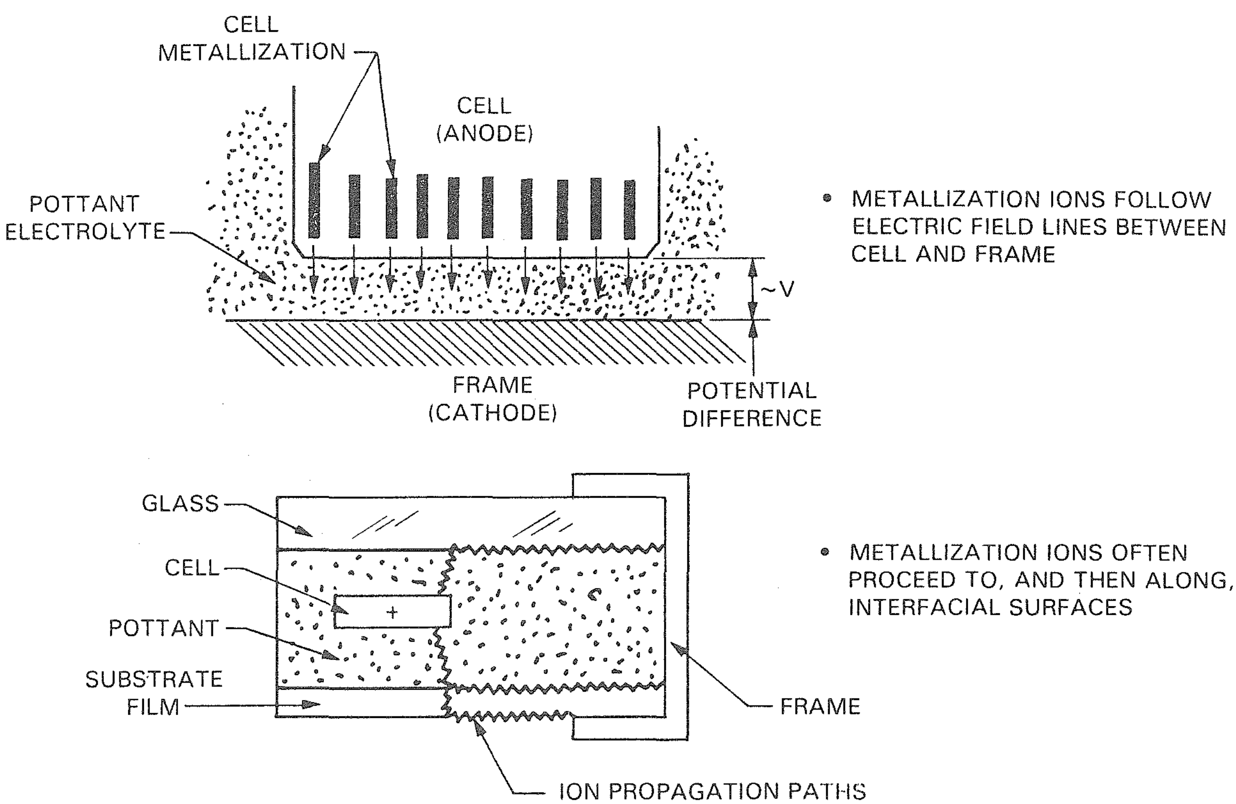


Figure 33. Schematic Representation of Electrochemical Corrosion

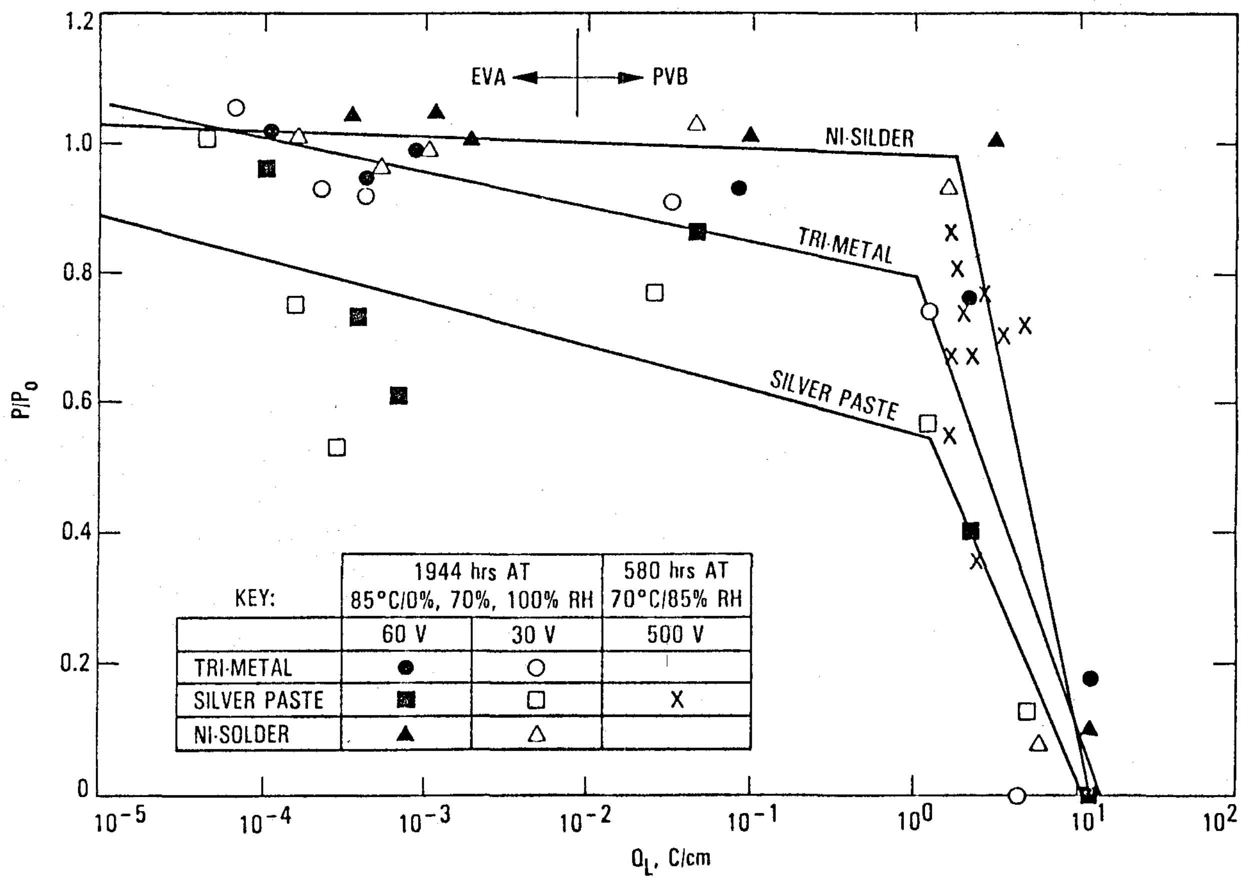


Figure 35. Cell Power Degradation (Final Power Divided by Initial Power) Versus Total Corrosion-Current Charge Transfer (Q_L)

(4) Developed data on probability of impact by various-sized hailstones, and means of surviving hail impact.

(5) Developed analysis tools and design data for the prediction of breaking load of glass sheets.

(6) Developed design data and testing techniques to determine fracture strength of crystalline-silicon wafers and cells.

(7) Developed test methods and performance data concerning reliability of solar-cell metallization systems.

(8) Developed analysis tools, test methods, and design data for control of solar-cell hot-spot heating.

(9) Developed design data and qualification testing techniques to ensure reliability of bypass diodes.

(10) Characterized electrical breakdown-strength of polymeric dielectric films.

(11) Characterized parameters involved in electrochemical corrosion of modules.

(12) Developed a comprehensive set of module qualification tests.

SECTION V

Module Development and Testing

A. BACKGROUND

Through the years, the FSA Project engaged in an extensive effort to develop the module technology (materials, processes, and reliability) required to meet the early-defined cost, efficiency, and lifetime goals. To measure technology progress, it was necessary to develop modules embodying the developed technology and to evaluate the modules. For this purpose, a series of five "block buys" of modules was conducted. This effort was supported by development of methods to: (1) conduct qualification tests, (2) perform accurate electrical measurements of module power, (3) perform failure analysis on modules, and (4) conduct field tests.

An important by-product of the block buys was the continuous transfer of technology directly into the companies manufacturing modules for the market. This process permitted the latest technology to become available not only in production modules, but also for procurement by the Project and by other DOE-sponsored organizations for use in large application experiments from which reports on module performance could be obtained. Throughout the life of the Project, the results from qualification tests, field tests, application experiments, and failure analyses were used in refinement of module design and test requirements and in identification of needs for engineering science and reliability-physics research. These interrelationships are shown in Figures 36 and 37.

B. THE BLOCK PROGRAM

The block buys consisted of a sequence of five module procurements: Block I through Block V (see Reference 7). In early 1976, at the infancy of the technology, Block I was a procurement of existing terrestrial modules from four manufacturers. This first module procurement was to establish the state of the art. The Block II procurement (Reference 125), initiated in late 1976 with higher performance and reliability standards, also involved four manufacturers. The Block III procurement (Reference 126), started in early 1978, consisted of large orders of modules (30 to 50 kW each) from five manufacturers. These essentially were production quantities of the Block II modules, with slightly revised specifications, needed for large applications projects. The Block IV program (Reference 127), initiated in 1980, included a pre-production phase that was followed, after satisfactory completion of qualification tests, by small production contracts. This program, which included more severe module requirements than the previous blocks, produced eight qualified designs from seven manufacturers. The Block V program (Reference 128), in response to yet more rigorous specifications, yielded successful designs from five contractors.

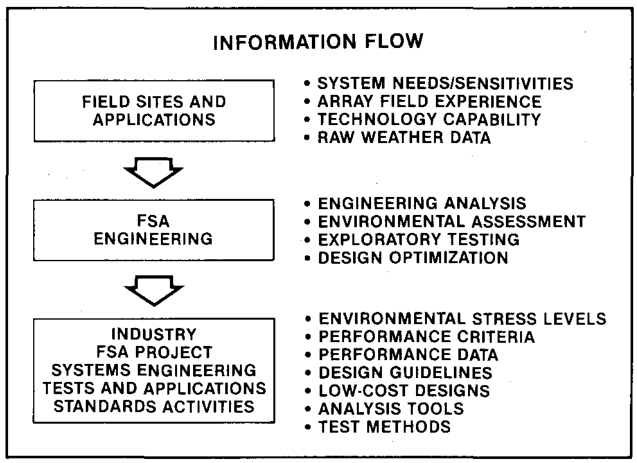


Figure 37. Information and Flow

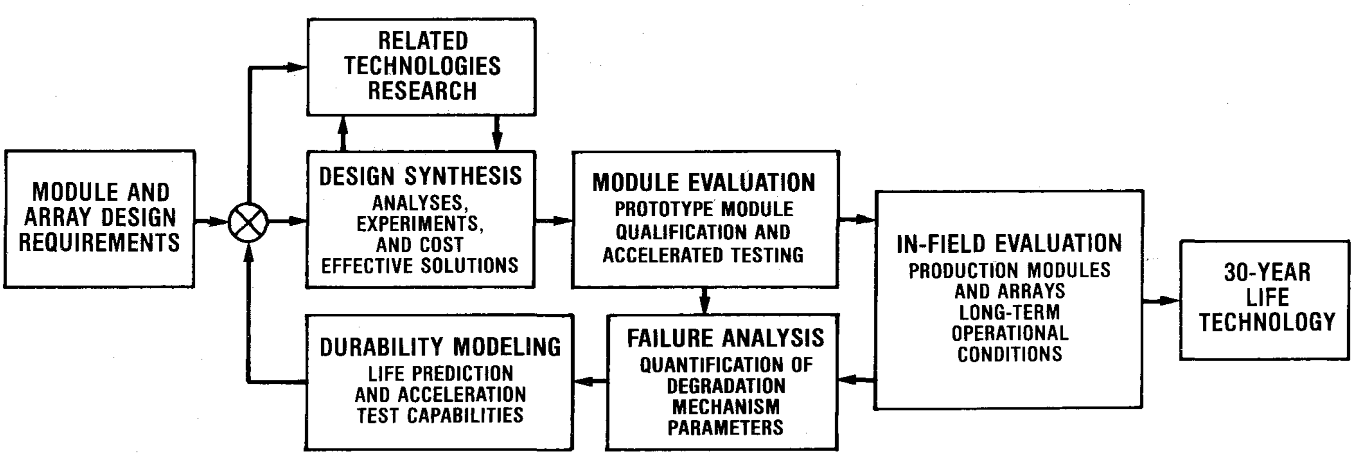


Figure 36. Module/Array Technology Development

The general model for the block program (see Reference 6) consists of the following sequence of events:

(1) FSA prepares design and test specification.

(2) FSA conducts competitive procurements culminating in award of parallel contracts.

(3) Contractor performs module design.

(4) FSA conducts design review.

(5) Contractor manufactures 10 modules.

(6) FSA performs module qualification tests (and failure analysis, as applicable).

(7) Contractor modifies design and/or processing procedure to correct problems revealed by qualification tests.

(8) FSA conducts design review.

(9) Contractor manufactures 10 modules.

(10) FSA performs module qualification tests (and failure analysis, as applicable).

(11) Contractor modifies design and/or processing as necessary and supplies modules for retest.

(12) FSA completes final testing.

(13) FSA prepares and issues User Handbook (see References 125 through 128) describing construction details and performance of successful module design by each contractor.

Principal ingredients responsible for the success of this approach are the competitive procurements, the FSA design-and-test specification, and the continuous cooperative interaction between FSA and the contractor. The competitive procurement provides incentive to incorporate the latest technology. The design and test specification identifies design improvements needed to improve performance, as revealed by results of prior qualification tests (from preceding block), field experience, and Project research. Interaction between FSA and the contractor is the means to apply all available technical resources to the guidance of the design and solution of problems. Not the least part of this interaction is the provision that FSA qualification tests and failure analysis provide the vehicle for unearthing and correcting flaws, rather than merely identifying success or failure.

1. Qualification Tests

The purpose of the qualification tests (see References 6 and 7) (Figure 38) was to assess the ability of the modules to withstand environmental and electrical stresses expected in the field. Because the most basic criterion for degradation is module power-output, preparation for the tests included a module characterization-phase that included the following measurements:

(1) Voltage and current temperature coefficients.

(2) NOCT.

(3) Current-voltage (I-V) characteristic.

After characterization and visual inspection, modules were subjected to two electrical tests:

(1) High-voltage isolation.

(2) Ground continuity.

The next events, a series of environmental tests, included:

(1) Temperature cycling.

(2) Humidity soak at high temperature.

(3) Mechanical load cycling.

(4) Hail impact.

(5) Twisted mounting surface.

After each test, module power output was measured and visual inspection was performed. After completion of all tests, the high-voltage isolation and ground continuity tests were repeated.

One additional test, Hot-Spot Endurance, was performed on a single, specially instrumented module set aside for this test only.

Among the unique environmental testing facilities that had to be developed to perform the above tests were hail guns, mechanical cyclic-loading apparatus (Figure 38), hot-spot test equipment, and test racks and instrumentation for NOCT.

Qualification tests were performed on more than 150 different module designs, including:

(1) Blocks I through V.

(2) Commercial (U.S. and foreign).

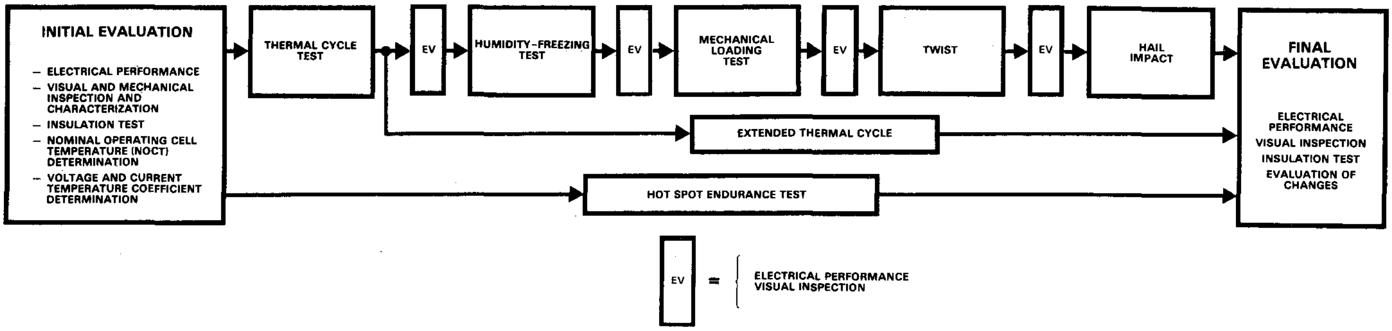
(3) DOE Residential Experiment Stations.

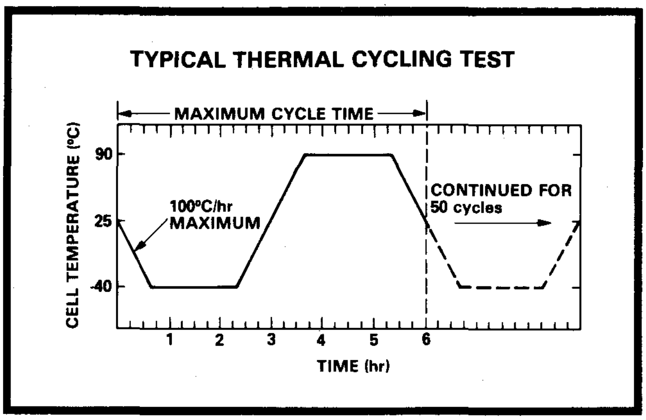
(4) Georgetown Project.

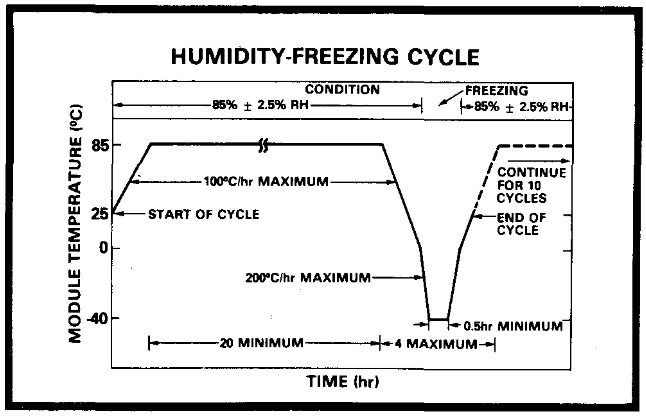
(5) India Project.

(6) SMUD Project.

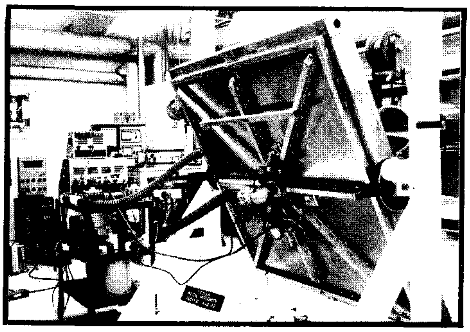
ELECTRICAL PERFORMANCE MEASURED AND PHYSICAL DURABILITY ASSESSED



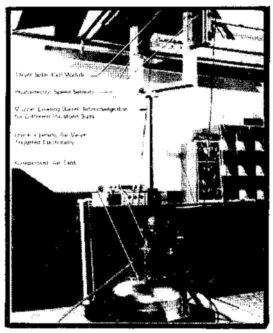




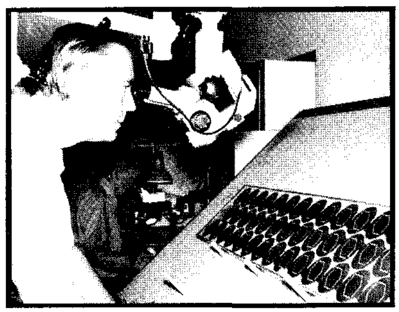
CYCLIC PRESSURE LOADING TEST APPARATUS



HAIL TEST APPARATUS



VISUAL INSPECTION



LARGE-AREA SOLAR SIMULATOR TESTING

QUALIFICATION TEST SPECIFICATIONS

TESTS	MODULES					TEST LEVELS
	BLOCK I	BLOCK II	BLOCK III	BLOCK IV* RES/IL	BLOCK V* RES/IL	
THERMAL CYCLE	50	50	50	50	50/200	-40°C TO +90°C, CYCLES AS INDICATED
HUMIDITY CYCLE	5	5	5	5	10	5 CYCLES AT 95% RH, 23°C TO 40°C OR 10 CYCLES AT 85% RH, -40°C TO +85°C
MECHANICAL LOADING CYCLE		100	100	10000	10000	2400 N/m^2 (50 lb/ft^2), CYCLES AS INDICATED
WIND RESISTANCE				X	X	UNDERWRITERS LAB TEST NO. 997 (Residential only)
TWIST		X	X	X	X	ONE CORNER LIFTED 2 cm/meter OF LENGTH
HAIL IMPACT				X	X	20 mm DIAMETER HAIL — 23 m/s
ELECTRICAL ISOLATION (volts)		1500	1500	1500/2000	1500/3000	50 μA MAX. CURRENT AT VOLTAGE INDICATED
GROUND CONTINUITY			X	X	X	50 milliohm MINIMUM RESISTANCE TO GROUND FOR EXPOSED CONDUCTORS
HOT-SPOT ENDURANCE					X	100 hr SHORT CIRCUITED AT NORMAL OPERATING CELL TEMPERATURE AND 100 mW/cm^2

* RES – RESIDENTIAL
IL – INTERMEDIATE LOAD

Figure 38. Module Qualification

These qualification tests provided internationally recognized assessments of PV module electrical performance and reliability that provided needed credibility for the developing PV industry.

2. Failure Analysis

When problems occurred during qualification tests or field tests, or at array installations, it was necessary to perform an in-depth failure analysis to find the exact cause of the problem. A Problem Failure Reporting system (Reference 129) was established by the FSA Project in 1975 to provide formal reporting of all failures, regardless of site of occurrence. This system reported about 1200 module failures. The reports and failed modules were delivered to failure-analysis personnel who then applied a variety of sophisticated techniques to isolate the specific cause of the failure (see Reference 10) (Figure 39). Some of these techniques were derived from the National Aeronautics and Space Administration (NASA) space exploration program and some were developed especially for the terrestrial PV program. A highly detailed report, describing each such analysis, presented the results along with recommendations for correcting the module deficiencies. These Performance and Failure Analysis Reports were supplied to the manufacturer of the module and to JPL personnel responsible for module-development research. Such analyses, performed on more than 435 modules, were instrumental in correcting design and processing problems to the extent that new modules incorporating the recommended changes then were successful in passing the qualification tests.

Among special test devices developed specifically for failure analysis of PV modules were the Sun-U-Lator (see Reference 9) and the Solar Cell Laser Scanner (Reference 130). The Sun-U-Lator is a test chamber in which illumination is applied cyclically to enable detection of module intermittent failures observed in the field during thermal stress changes. The Solar Cell Laser Scanner provides a laser sweep of an entire module. The output photocurrent produces a two-axis image on a cathode ray tube (CRT). The image appears as a photograph of the module, with an intensity pattern showing the performance of every cell, as affected by anomalies such as cell cracks, variations in shunt resistance, and circuit discontinuities.

3. Field Tests

From the initiation of the Project, it was obvious that data on performance of modules in the field were necessary to identify both research needs and technology progress. In 1976, JPL set up four field test sites in California. In 1977, NASA Lewis Research Center set up 12 sites in the contiguous United States, Alaska, and the Panama Canal Zone. Modules supplied by JPL were deployed at all 16 sites (Figure 40). In 1979, the Lewis sites were turned over to JPL. This complex of 16 sites provided a broad variety of environments: mountain, desert, marine, hot and dry, hot and humid, cold, moderate, windy, and high pollution (Reference 131).

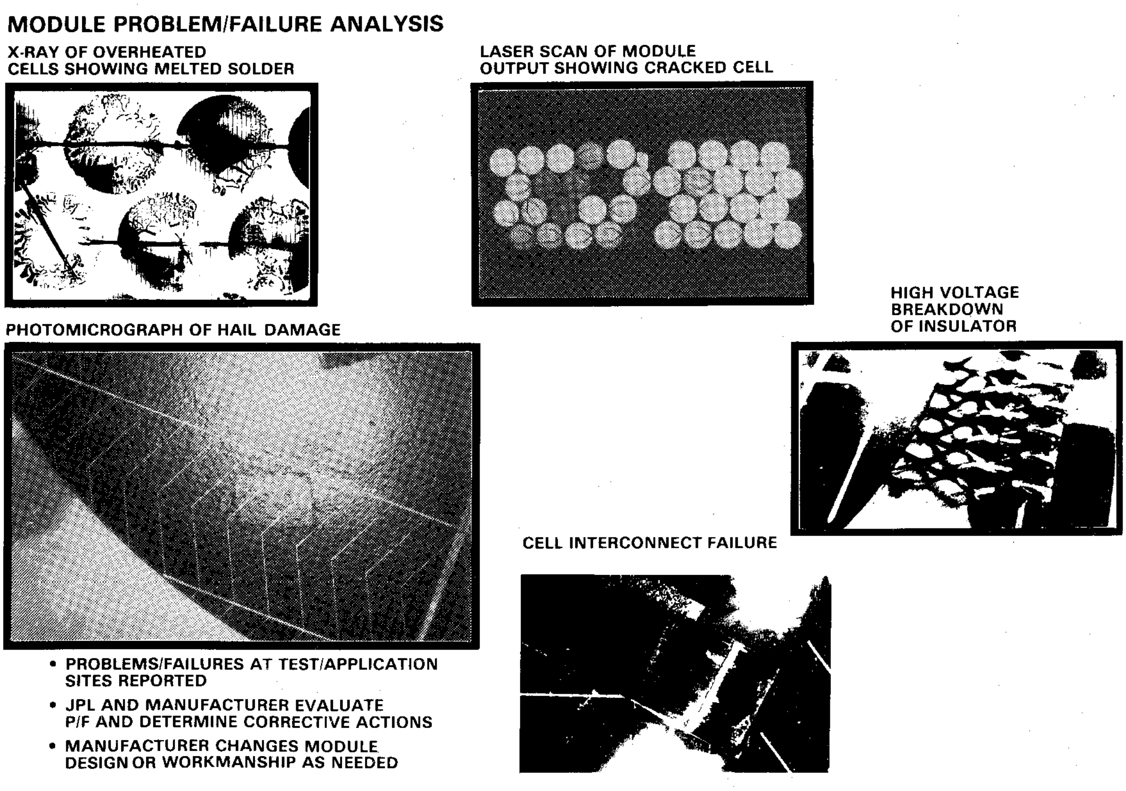
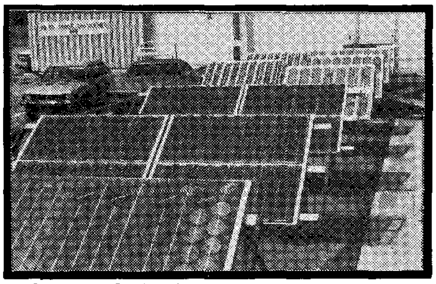


Figure 39. Module Problem/Failure Analysis

MODULE FIELD TESTING-16 SITES



PASADENA, CA (JPL)
PRIME SITE FOR FIELD
TESTING

HOUGHTON, MI
TYPICAL REMOTE SITE

FIELD TEST SITES

EXTREME WEATHER
- FORT GREELY, ALASKA (ARCTIC)
- FORT CLAYTON, CANAL ZONE (TROPIC)

MARINE
- KEY WEST, FLORIDA
- SAN NICOLAS ISLAND, CALIFORNIA
- POINT VICENTE, CALIFORNIA

HIGH DESERT
- ALBUQUERQUE, NEW MEXICO
- DUGWAY, UTAH
- GOLDSTONE, CALIFORNIA

MOUNTAIN
- MINES PEAK, COLORADO
- TABLE MOUNTAIN, CALIFORNIA

URBAN COASTAL
- NEW ORLEANS, LOUISIANA
- NEW LONDON, CONNECTICUT

MIDWEST
- CRANE, INDIANA

UPPER GREAT LAKES
- HOUGHTON, MICHIGAN

NORTHWEST
- SEATTLE, WASHINGTON

URBAN SOUTHWEST
- PASADENA, CALIFORNIA

Figure 40. Module Field Testing (16 Sites)

Modules were deployed at the field sites as they became available from Blocks I, II, and III procurements. Periodically, the modules at these sites were visited by a JPL team to perform visual inspection for mechanical degradation and to measure electrical performance. These visits identified problems that then were solved by improvements in design, materials, and processes. Statistical data on failure rates showed essentially a stepwise improvement from block to block (Reference 132).

In 1981, a reduction in Project funding and the desire to detect problems early in the test period led to a new plan (Reference 133) that involved the closing of most of the test sites. Only four sites were retained. Some Block IV modules were installed at three of these sites and the prior program of occasional monitoring was continued. At the remaining site (at JPL), Block IV modules were set up in system configurations and an automated data collection system was developed to provide daily monitoring of performance. Further budget restrictions led to restructuring of the JPL site so that data-taking did not begin until the beginning of 1983. Additional budget cuts resulted in termination of regular operations in 1984.

Although statistics have not been compiled for the Block IV modules, none have failed during the approximately 2 years that the modules have been in the field.

4. Application Experiments

In support of the DOE program to establish application experiments to test PV modules within the system context, the FSA Project supplied about 11,000 modules (from Blocks I, II, and III) for installation in systems at many locations in the United States. Systems ranged in size from the 1.5 kW system at the Chicago Museum of Science and Industry to the 100 kW system at National Bridges National Monument (Reference 134). One such system is shown in Figure 41.

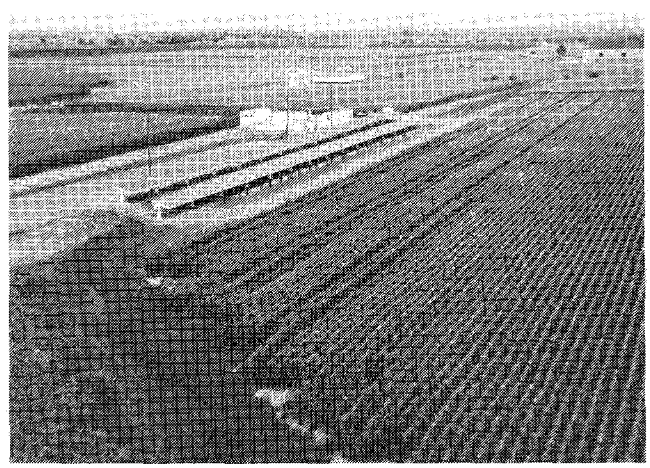


Figure 41. PV Application Experiment

These application experiments, monitored by MIT Lincoln Laboratory, included inspection of modules and removal of failed modules that then were sent to FSA for failure analysis. Results of these analyses were supplied to module manufacturers as part of the effort to motivate improvements in design and processing to correct deficiencies found in the field.

5. Electrical Performance Measurements

Because the basic criterion for PV module efficiency and degradation is the measurement of electrical performance, it was necessary to develop an accurate means of performing these measurements. A low-cost method of measurement was needed because every production module had to be measured. Although a standard irradiance (magnitude and spectral distribution) was defined, no solar simulator existed that could duplicate the standard spectrum. Measurement under natural sunlight did not solve the problem because the terrestrial solar spectrum is a function of atmospheric conditions, the necessary atmospheric conditions do not commonly occur, and instrumentation to verify the existence of these conditions is prohibitively complex.

A variety of solar simulators existed, but none of these provided the standard spectrum and most were not spectrally stable. One solution to the problem was to calibrate a standard reference cell for each manufacturer. The reference cell was made from a cell, chosen to represent the spectral response of the modules produced by that manufacturer. A primary calibration was performed on the cell under natural sunlight during a period when the standard spectral irradiance occurred. Measurement of a module then could be performed by first exposing the reference cell to the simulator and adjusting the simulator output to equal the calibration value for that cell. Under the assumption that the spectral response of the reference cell closely matches the spectral response of the module, it could be shown that accurate module power measurements could be obtained relatively independent of the spectrum of the simulator.

One disadvantage of the above scheme was that it required a different reference cell for each manufacturer's product and the primary calibration of the cell was costly and could take several months. This problem was solved by designing a simulator/filter combination that produced the standard spectrum. Such a system has now been implemented for both of the presently used U.S. standard irradiances: the air mass 1.5 direct normal irradiance (ASTM E 891-82), and the air mass 1.5 global spectrum, combining direct and diffuse components of the spectrum (ASTM E 892-82). With this system, highly accurate measurements can be obtained without the need for a reference cell spectrally matched to the module.

The simulator used in this system, known as the Large-Area Pulsed Solar Simulator (LAPSS) (see Reference 46), produces the spectrum shown in Figure 42 when it is not filtered. The filtered spectra for the direct normal case and the global case are shown in Figures 43 and 44, respectively, along with the desired standard spectra. These spectral matches are close enough in both cases so that the module measurement error caused by the mismatch is no greater than 1 % even without a spectrally-matched reference cell. Therefore, when filtered to the desired reference spectrum, the LAPSS can be used without design-specific reference cells to perform secondary calibration of additional reference cells, and to measure modules made of any present type of silicon cell.

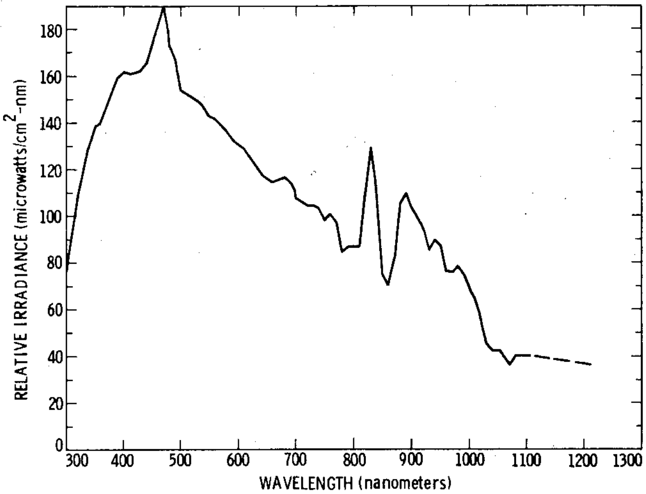


Figure 42. Spectral Irradiance (JPL Unfiltered LAPSS)

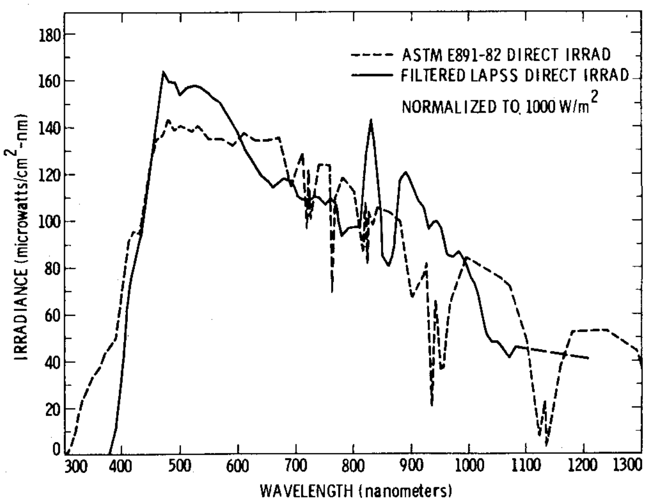


Figure 43. Spectral Irradiance (AM1.5 Direct LAPSS Versus ASTM AM1.5 Direct)

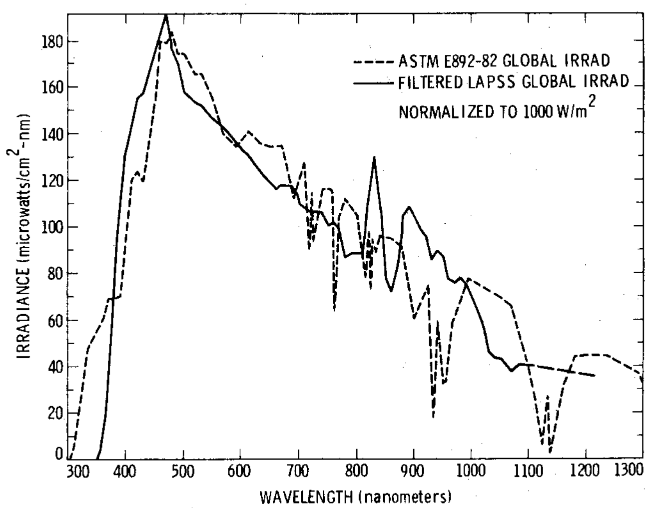


Figure 44. Spectral Irradiance (AM1.5 Global LAPSS Versus ASTM AM1.5 Global)

Before the secondary calibration capability existed, primary (outdoor) calibration was performed on reference cells from most U.S. manufacturers. These have been in use as industry standards for many years. Subsequently, the secondary calibration method has been used to calibrate cells and modules for many manufacturers and laboratories in the United States and many foreign countries.

In efforts to promote this measurements technology, the Project engaged in international round-robin measurement exercises and participated in the ASTM Standards Committee that defined the above-mentioned irradiance models, calibration procedures, and reference cell design.

6. Quality Assurance

During the first few years of the program, several new photovoltaic companies were founded to develop and exploit the evolving terrestrial PV technology. Because most of the work was developmental, these companies had no initial needs for formal quality assurance (QA) practices or organizations. With the initiation of the block buys, it became necessary to introduce these practices into the operations of the contractors to establish the control of product quality necessary to determine or evaluate progress, and also necessary to ensure that the large quantities of modules to be supplied for the field test sites and for the application experiments were acceptable.

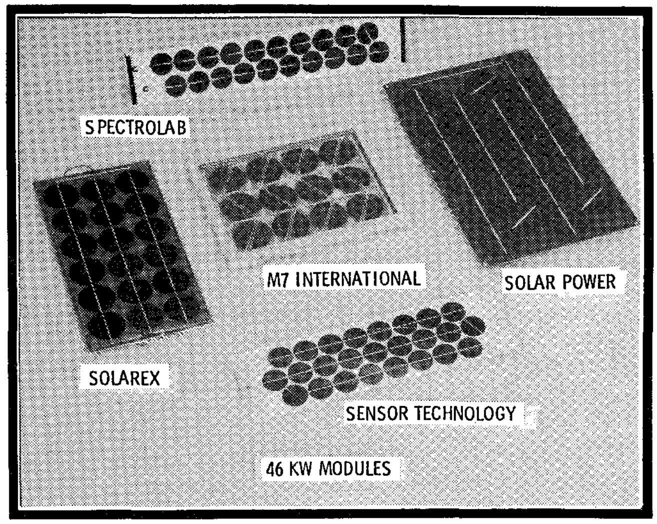
To meet the above objectives, FSA QA personnel played a key role in developing criteria and in training contractor personnel. The block contracts required that the contractors prepare QA plans for FSA approval. It was required that these plans show the role of QA in the production process, include inspection criteria (Reference 135) for the modules, and provide for FSA review and approval of these QA operations and for review and approval of the method of performing electrical measurements of module performance. Where large production orders were involved, FSA inspectors were in residence at the contractor sites and performed acceptance inspection there.

The QA organization also played vital roles in qualification test programs and field test programs. During qualification tests, they inspected every module before and after every step in the tests (see Figure 38). In the field test program, they periodically visited the 16 sites and inspected all modules.

In summary, the QA operation was successful in promoting high standards in module production and in serving the development of reliable modules.

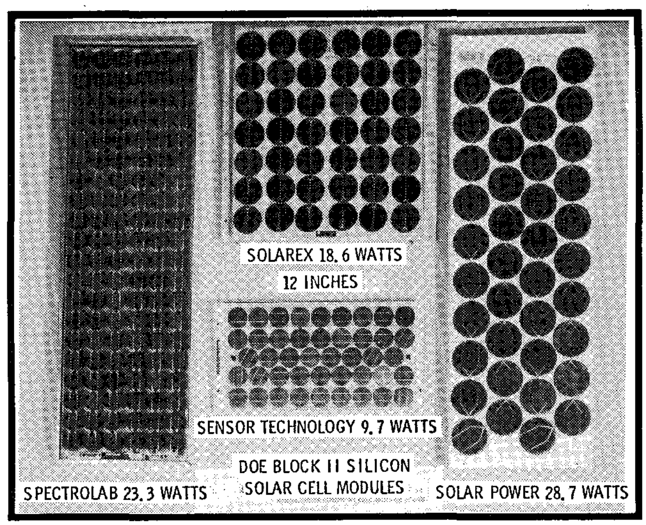
C. MODULE EVOLUTION

The five block buys of modules (Figures 45 through 49) were successful in motivating continual improvements throughout the course of the Project. Although the initial Block I modules were quite inefficient, producing less than 10 W, with little expectation of durability, the final Block V modules produced as much as 185 W, and have expected life in excess of 20 years. The Block V modules have found application in megawatt utility power plants (Figure 50). An immediate appreciation of this growth can be experienced by viewing Figure 51, in which an observer views a Block I module against a background assembly of four Block V modules.



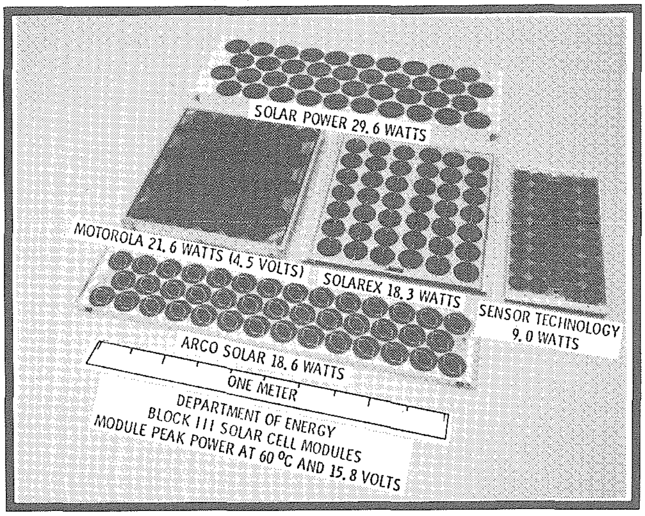
- ENVIRONMENTAL TESTS LIMITED TO:
  TEMPERATURE CYCLE
  HUMIDITY SOAK
- MANY DESIGN IMPROVEMENTS DURING PRODUCTION
- ELECTRICAL PERFORMANCE PER MANUFACTURERS RATINGS

Figure 45. Block I: 1975 to 1976, Off-the-Shelf Design, 54 kW



- FIRST LAMINATED MODULE
- CELL INTERCONNECT AND TERMINAL REDUNDANCY
- QA SPECIFICATION INTRODUCED
- ELECTRICAL PERFORMANCE CRITERIA (15.8 VOLTS – 60°C CELL TEMPERATURE)
- STANDARD ARRAY SIZE AND MOUNTING
- INTRODUCTION OF GROUNDING SAFETY PROVISIONS
- EXPANDED ENVIRONMENTAL QUALIFICATION TESTING
  - THERMAL CYCLE
  - HUMIDITY CYCLE
  - STRUCTURAL LOADING

Figure 46. Block II. 1976 to 1977, Designed to FSA Specifications, 127 kW



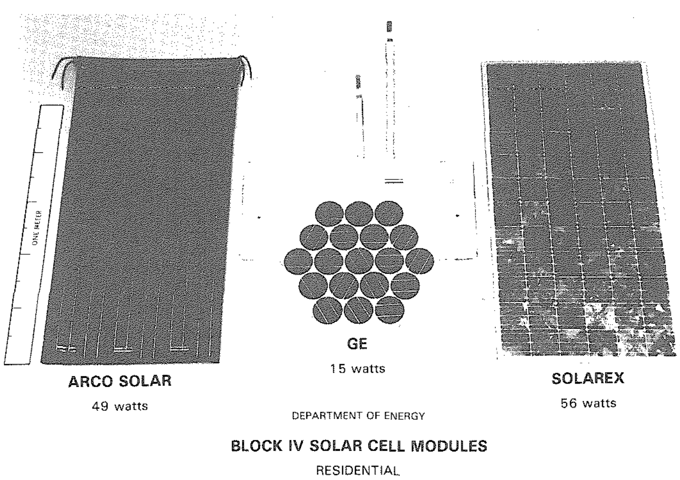
- DESIGN AND TEST SPECIFICATIONS ESSENTIALLY SAME AS BLOCK II
- IMPROVEMENTS IN DESIGN AND PRODUCTION PROCESSES RESULTING FROM BLOCK II EXPERIENCE
- MORE UNIFORM QA STANDARDS

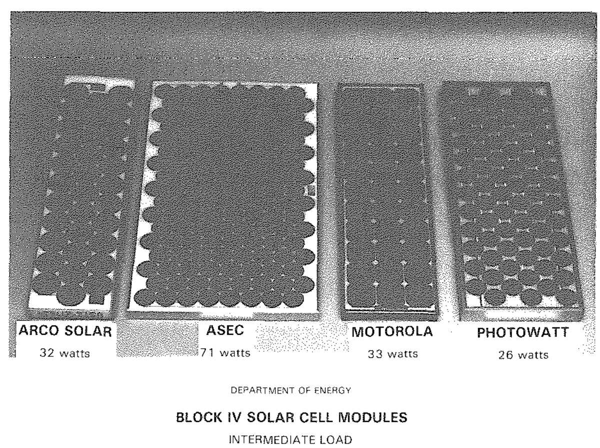
Figure 47. Block III: 1978 to 1979, Similar Specifications to Block II, 259 kW

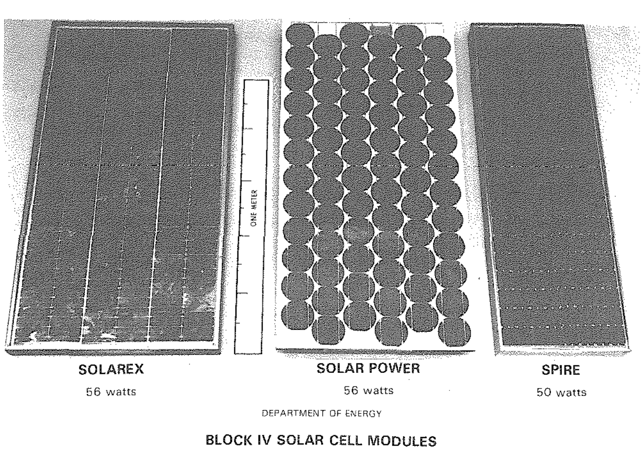
Representative examples of the Block I through Block V modules are shown in Figure 52. Table 7 lists representative characteristics of each block of modules (see Reference 7). The photograph, the list of characteristics, and the five trend charts (Figures 53 through 57) portray the evolution and progress, during this program, of flat-plate modules with crystalline-silicon cells. Characteristics of all block-buy modules that passed qualification tests are given in Tables 8 through 10 (References 6, 125 through 128, and 136).

High-Efficiency Modules

Although maximum module efficiency increased from about 6% in Block I to about 11% in Block IV, no additional increase in efficiency came out of Block V. During this period, however, advances in efficiency of very small experimental cells encouraged hope that improvements could be scaled up to the large-area cells and lead to higher module efficiency. Accordingly, a contract was given to Spire Corp. to work toward the DOE goal of a 15% efficient module. This effort was successful. In 1986, a 75.2-W module with 15.2% efficiency (Reference 137), was assembled

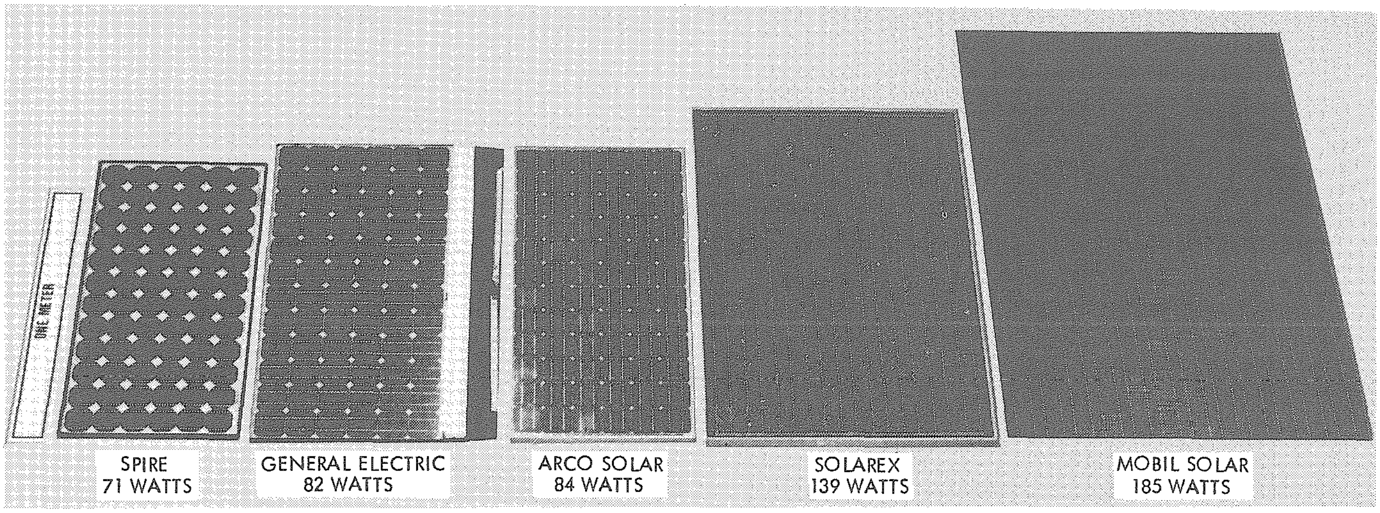






- TYPICAL DESIGN FEATURES
  - LAMINATED MODULE CONSTRUCTION
  - FAULT TOLERANT CELL AND CIRCUIT DESIGNS
  - LARGER POWER OUTPUT
  - CELLS WITH BACK SURFACE FIELDS
  - GLASS FRONT FACE
- INNOVATIVE DESIGN FEATURES
  - SHAPED CELLS
  - ION IMPLANTED CELLS
  - SEMICRYSTALLINE CELLS
  - ETHYLENE VINYL ACETATE ENCAPSULANT
  - BATTEN — SEAM ROOFING SUBSTRATE
  - FRAMELESS MODULE
  - INTEGRAL BYPASS DIODES

Figure 48. Block IV: 1980 to 1981, Industry Designs Reviewed by FSA, 26 kW of Prototype Modules



- TYPICAL DESIGN FEATURES
  - LARGER POWER OUTPUT
  - MODULE EFFICIENCY > 10% (EXCEPT RIBBON CELL MODULE)
  - GLASS TOP COVER
  - ETHYLENE VINYL ACETATE ENCAPSULANT
  - LAMINATED COMPOSITE FILM BACK COVER
  - LAMINATED MODULE CONSTRUCTION
  - FRAMELESS MODULE
  - SHAPED CELLS (HIGHER PACKING FACTOR)
  - PARALLEL CELL STRINGS
  - FAULT TOLERANT CELL AND CIRCUIT DESIGNS
  - BYPASS DIODES

- INNOVATIVE DESIGN FEATURES
  - MAJOR INCREASE IN AREA AND POWER OUTPUT
  - MET MORE STRINGENT QUALIFICATION TESTS
  - VIRTUAL ELIMINATION OF THE FOLLOWING CATASTROPHIC FAILURE MODES
    - UNACCEPTABLE CELL CRACKS
    - INTERCONNECT FAILURES
    - HOT-SPOT FAILURES
    - HAIL DAMAGE
  - MODULE WITH CELLS MADE FROM SILICON RIBBON (EFG) GROWN TO THE CORRECT THICKNESS

Figure 49. Block V: 1981 to 1985, Industry Designs Reviewed by FSA, Small Quantities for Evaluation Only

from cells with an average efficiency of about 17.5%. The module, shown in Figure 58, was made of cells fabricated using float-zone (FZ) silicon. FZ-silicon can be made more pure than that produced by the more common, and presently less expensive Czochralski (Cz) process. Equally efficient cells, made with Cz-grown silicon, also have been demonstrated by Spire. This fact, plus evidence that Spire can produce large-area (50 cm^2) cells of 18.5% efficiency, indicate that 15% module efficiency can be achieved in low-cost production modules.

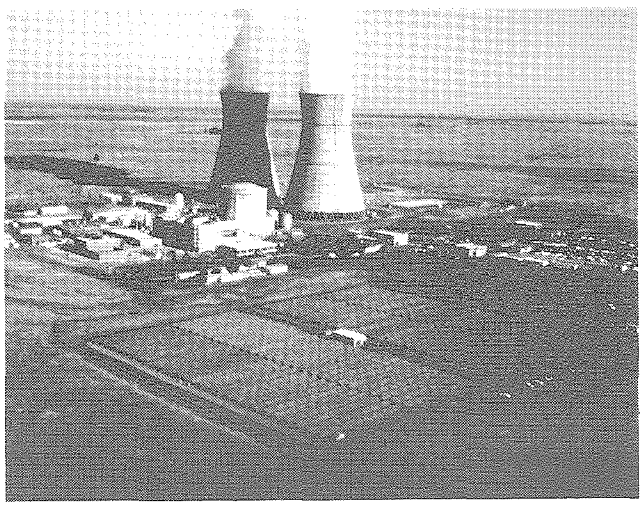


Figure 50. Utility PV Power Plant

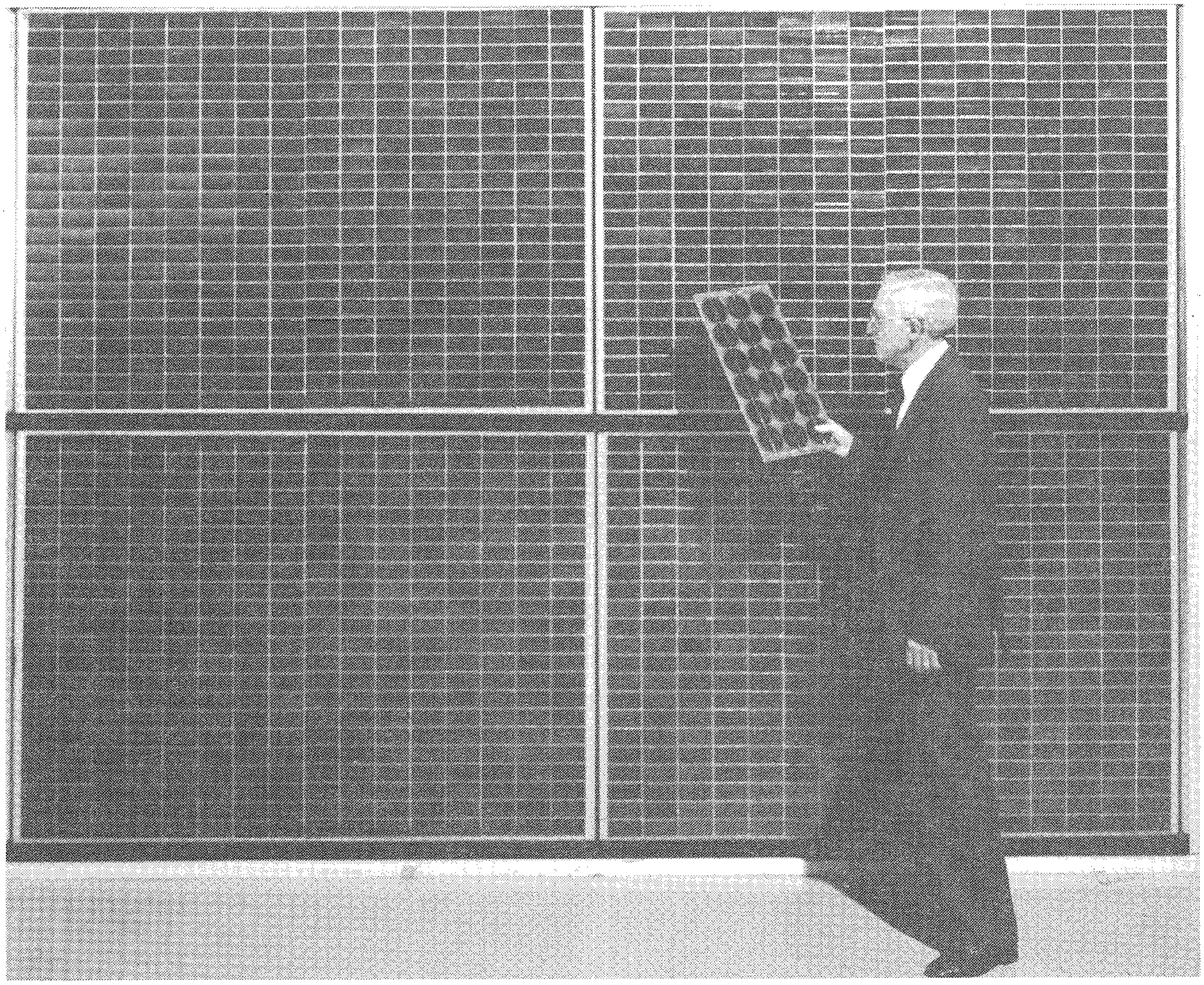


Figure 51. Comparison of Block I to V Modules

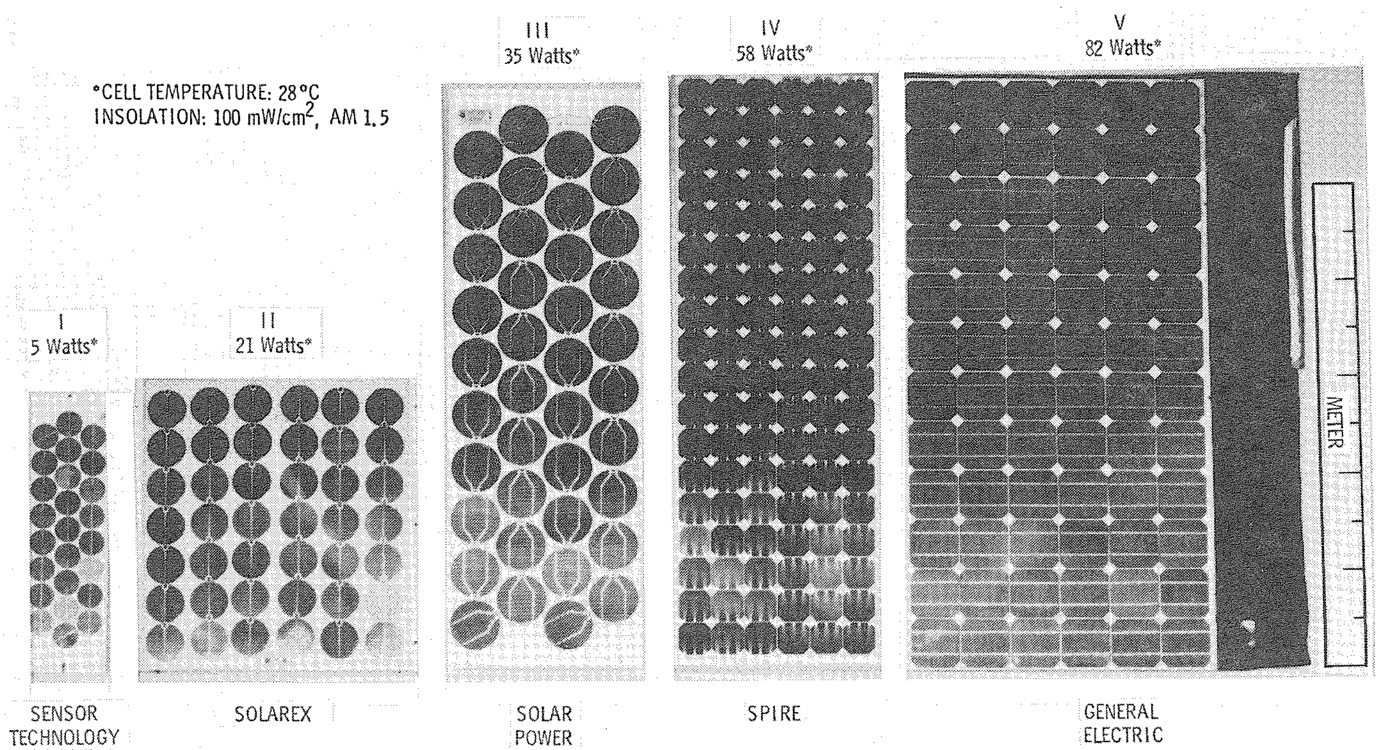


Figure 52. Representative Examples of Block I through V Modules

Table 7. Representative Characteristics of Block Modules

	I	II	III	IV	V
AREA (m^2)	0.1	0.4	0.3	0.6	1.1
WEIGHT (kg)	2	5	5	9	17
SUPERSTRATE OR TOP COVER	SILICONE RUBBER	SILICONE RUBBER	SILICONE RUBBER	GLASS	GLASS
SUBSTRATE OR BOTTOM COVER	RIGID PAN	RIGID PAN	RIGID PAN	FLEXIBLE SHEET	FLEXIBLE LAMINATE
FRAME	NO	YES	YES	YES	NO
CONNECTIONS	TERMINALS	J-BOX	TERMINALS	PIGTAILS	PLUG-IN
ENCAPSULATION SYSTEM	CAST	CAST	CAST	LAMINATED	LAMINATED
ENCAPSULATION MATERIAL	SILICONE RUBBER	SILICONE RUBBER	SILICONE RUBBER	PVB	EVA
CELLS					
QUANTITY	21	42	43	75	117
SIZE (mm)	DIA: 76	DIA: 76	DIA: 76	95 x 95	100 x 100
CONFIGURATION	ROUND	ROUND	ROUND	SHAPED	SHAPED
MATERIAL	CZ	CZ	CZ	CZ	CZ
JUNCTION	N/P	N/P	N/P	N/P P^+	N/P
FAULT TOLERANCE					
PARALLEL CELL STRINGS	NONE	NONE	NONE	3	6
INTERCONNECT REDUNDANCY	NONE	MINOR	MINOR	MUCH	MUCH
BY-PASS DIODES	NO	NO	NO	YES	YES
PACKING FACTOR	0.54	0.60	0.65	0.78	0.89
NOCT[a]	43	44	48	48	48
PERFORMANCE AT 28°C CELL TEMP.[b]					
POWER, MAX. (W)	8	24	26	54	112
MODULE EFFICIENCY (%)	5.8	6.7	7.4	9.1	10.6
ENCAPSULATED CELL EFFICIENCY (%)	10.6	11.2	11.5	11.8	12.3

[a]NOMINAL OPERATING CELL TEMPERATURE: CELL TEMPERATURE IN OPEN-CIRCUITED MODULE EXPOSED TO 80 mW/cm^2 INSOLATION IN AMBIENT OF 20°C, 1 m/s WIND VELOCITY.

[b]AT 100 mW/cm^2, AM 1.5 INSOLATION.

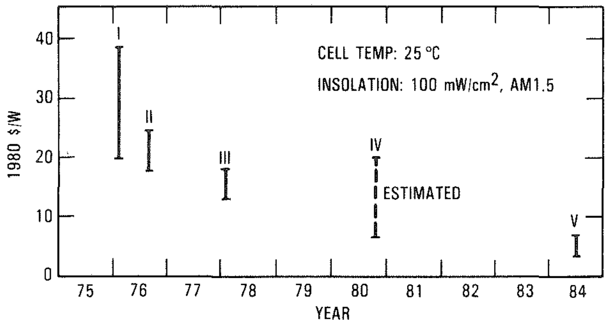


Figure 53. Module Cost Trend

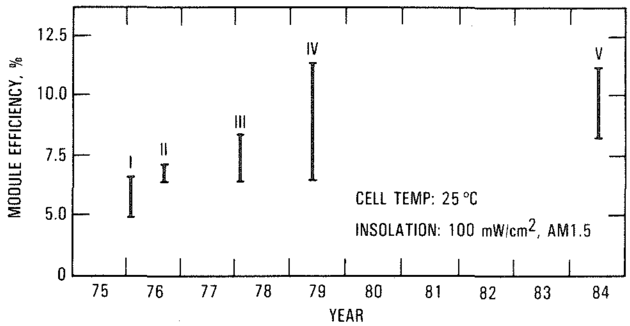


Figure 54. Module Efficiency Trend

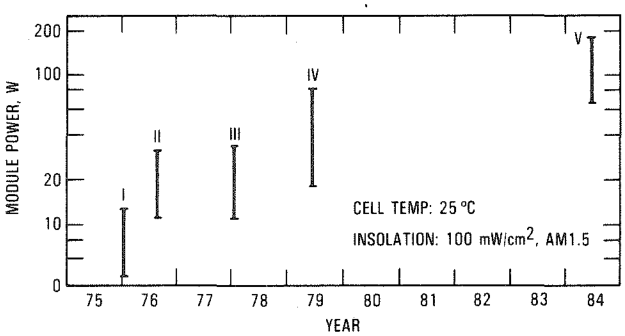


Figure 55. Module Power Trend

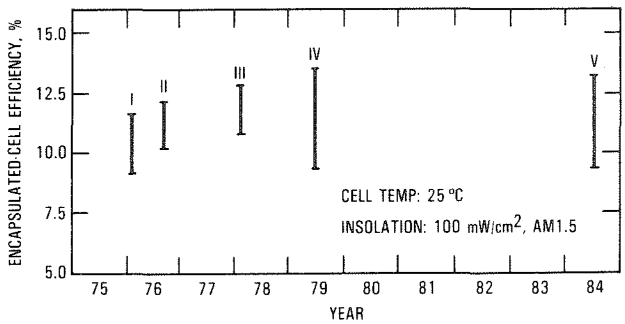


Figure 56. Cell Efficiency Trend

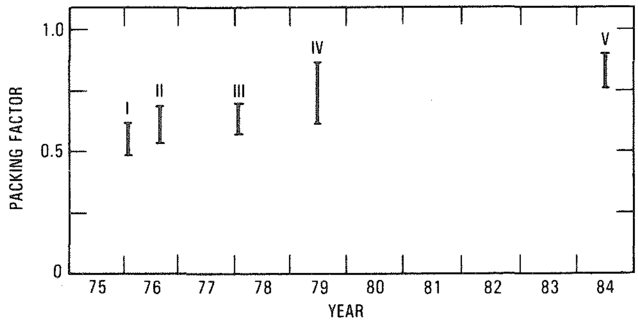


Figure 57. Packing Factor Trend

Table 8. Module Cell and Circuit Characteristics

			CELL					CIRCUIT			
	MANUFACTURER	MODEL NO.	QNTY	SIZE (mm)	SHAPE	BASE MATL	JUNCTION	SERIES CELLS	PARALLEL CELLS	CROSS TIES	BY-PASS DIODES
I	SENSOR TECH.	V-13-AT	25	50 DIA	ROUND	CZ	N/P	25	–	–	–
	SOLAREX	785	18	76 DIA			N/P	18	–	–	–
	SOLAR POWER	E-10-229-1.5	22	87 DIA			P/N	22	–	–	–
	SPECTROLAB	060513-8	20	50 DIA			N/P	20	–	–	–
II	SENSOR TECH.	20-10-1452-J	44	56 DIA				44	–	–	–
	SOLAREX	A-0221-D	42	76 DIA				42	–	–	–
	SOLAR POWER	E-10008-C	40	102 DIA			P/N	40	–	–	–
	SPECTROLAB	022962-G	120	50 DIA			N/P	40	3	–	–
III	ARCO SOLAR	10699-C	41	76 DIA				41	–	–	–
	MOTOROLA	P-0170-770-J	48	76 DIA				12	4	11	–
	SENSOR TECH.	20-10-1646	44	56 DIA				44	–	–	–
	SOLAREX	A-0221-G	42	76 DIA	ROUND W/1 FLAT			42	–	–	–
	SOLAR POWER	E-10008-F	40	102 DIA	ROUND		P/N	40	–	–	–
IV	ARCO SOLAR	012110-E	35	103 DIA	ROUND W/2 FLATS		N/P	35	–	–	1
	ASEC	60-3062-F	136	76 DIA	ROUND			34	4	5	1
	G.E.[a]	47J254977G1-C	19	100 DIA	ROUND W/1 FLAT			19	–	–	–
	MOTOROLA	MSP43D40-G	33	100 x 100	QUASI-SQUARE		N/P P+	33	–	–	–
	PHOTOWATT	ML-1961-D	72	76 DIA	ROUND			12	6	–	–
	SOLAREX	580-BT-L-C	72	95 x 95	SQUARE	SEMI-XTL		36	2	35	36
	SOLAREX[a]	580-BT-R-C	72	95 x 95	SQUARE	SEMI-XTL		12	6	11	12
	SPIRE	058-0007-A	108	64 x 64	QUASI-SQUARE	CZ		36	3	11	2
V	ARCO SOLAR	004-014168-2	72	97 x 97	QUASI-SQUARE	CZ	N/P	12	6	3	1
	G.E.[a]	47E258449G2-A	72	100 x 100	QUASI-SQUARE	CZ	N/P	36	2	34	3
	MSEC[a]	Ra-180-12-D	432	95 x 48	RECTANGULAR	EFG	N/P	36	12	2	1
	SOLAREX	C-120-10A	117	101 x 101	RECTANGULAR	SEMI-XTL	N/P	13	9	–	1
	SPIRE[a]	058-0008-B	72	91 x 91	QUASI-SQUARE	CZ	N/P-P+	36	2	2	3

NOTE: [a]RESIDENTIAL MODULE

Table 9. Module Performance Characteristics

			SAMPLE PERFORMANCE																
			AT 100 mW/cm², AM 1.5, 28°C CELL TEMP.								AT 100 mW/cm², AM 1.5, NOCT[b]								
	MANUFACTURER	MODEL NO.	P_{max} (W)	$V_{P_{max}}$ (V)	$I_{P_{max}}$ (A)	V_{oc} (V)	I_{sc} (A)	FILL FACTOR	MODULE EFF. (%)	CELL EFF.[c](%)	P_{max} (W)	$V_{P_{max}}$ (V)	$I_{P_{max}}$ (A)	V_{oc} (V)	I_{sc} (A)	FILL FACTOR	MODULE EFF. (%)	CELL EFF.[c](%)	NOCT[b] (°C)
I	SENSOR TECH.	V-13-AT	4.7	9.8	0.48	DATA NOT AVAILABLE			4.8	9.4	DATA NOT AVAILABLE								39
	SOLAREX	785	8.7	7.0	1.24				6.5	10.6									48
	SOLAR POWER	E-10-229-1.5	13.2	9.6	1.38				5.8	10.2									49
	SPECTROLAB	060513-8	4.7	9.4	0.50				5.9	12.0									35
II	SENSOR TECH.	20-10-1452-J	11.4	20.7	0.55	24.8	0.60	0.77	6.8	10.6	10.4	18.7	0.56	23.4	0.59	0.75	6.3	9.6	43
	SOLAREX	A-0221-D	20.5	18.0	1.14	24.3	1.43	0.59	6.0	10.7	18.7	16.3	1.15	22.4	1.44	0.58	5.5	9.8	47
	SOLAR POWER	E-10008-C	33.8	18.0	1.88	23.5	1.98	0.73	7.4	10.7	31.3	16.6	1.89	22.0	1.98	0.72	6.9	9.7	46
	SPECTROLAB	022962-G	30.0	18.2	1.65	23.0	1.86	0.70	6.6	12.7	28.5	17.3	1.65	21.9	1.88	0.69	6.3	11.7	41
III	ARCO SOLAR	10699-C	22.8	18.2	1.25	23.3	1.38	0.71	8.4	12.2	20.6	16.5	1.25	22.0	1.40	0.67	7.6	11.0	50
	MOTOROLA	P-0170-770-J	26.2	5.9	4.45	7.1	4.82	0.76	7.7	11.8	23.6	5.3	4.45	6.6	4.88	0.73	7.0	10.8	53
	SENSOR TECH.	20-10-1646	11.3	20.2	0.56	24.6	0.62	0.74	6.8	10.5	10.2	18.6	0.55	23.0	0.62	0.72	6.1	9.4	43
	SOLAREX	A-0221-G	21.7	17.8	1.22	23.7	1.40	0.65	6.5	11.6	19.7	16.4	1.20	22.1	1.41	0.63	5.8	10.4	46
	SOLAR POWER	E-10008-F	34.8	18.3	1.90	23.6	1.97	0.75	7.7	11.2	32.2	17.2	1.87	22.0	1.98	0.74	7.1	10.3	46
IV	ARCO SOLAR	012110-E	35.7	16.6	2.15	21.0	2.42	0.70	9.6	12.6	32.4	15.0	2.16	19.6	2.42	0.68	8.7	11.4	46
	ASEC	60-3062-F	84.6	16.5	5.11	20.2	5.40	0.78	10.1	13.6	77.4	15.0	5.16	19.2	5.45	0.74	9.3	12.6	47
	G.E.[a]	47J254977GI-C	18.8	8.5	2.21	11.0	2.53	0.68	9.6	12.6	15.3	7.1	2.16	9.6	2.53	0.63	7.8	10.3	58
	MOTOROLA	MSP43D40-G	37.3	16.2	2.30	19.5	2.50	0.76	8.8	11.6	34.3	15.1	2.27	18.4	2.52	0.74	8.1	10.6	49
	PHOTOWATT	ML-1961-D	38.6	5.68	6.79	6.98	7.58	0.73	7.2	11.6	34.9	5.10	6.84	6.5	7.62	0.70	6.6	10.6	47
	SOLAREX	580-BT-L-C	62.6	16.1	3.90	19.6	4.50	0.71	8.2	9.6	57.3	14.4	3.98	18.1	4.58	0.69	7.5	8.8	49
	SOLAREX[a]	580-BT-R-C	60.8	5.31	11.4	6.60	13.2	0.69	8.1	9.3	54.5	4.70	11.6	6.2	13.3	0.66	7.3	8.4	56
	SPIRE	058-0007-A	57.0	16.2	3.52	20.3	3.64	0.77	11.4	13.6	50.8	14.2	3.58	18.6	3.67	0.74	10.1	11.9	49
			AT 100 mW/cm², AM 1.5, 25°C CELL TEMP.								AT 100 mW/cm² AM 1.5, NOCT[b]								
V	ARCO SOLAR	004-014168-2	84.1	5.82	14.5	7.16	15.9	0.74	11.3	12.6	75.0	5.20	14.4	6.56	16.1	0.71	10.1	11.2	49
	G.E.[a]	47E258449G2-A	81.7	17.0	4.81	20.9	5.65	0.69	10.5	11.7	65.4	13.3	4.92	17.7	5.69	0.65	8.4	9.3	65
	MSEC[a]	Ra-180-12-D	185.	15.3	12.1	18.9	13.3	0.74	8.4	9.4	165.	13.2	12.5	17.9	13.7	0.67	7.5	8.4	48
	SOLAREX	C-120-10A	139.	5.84	23.8	7.47	26.7	0.70	10.3	11.7	123.	5.18	23.7	6.79	27.2	0.67	9.1	10.3	48
	SPIRE[a]	058-0008-B	70.7	16.1	4.39	20.7	4.79	0.71	10.1	13.3	62.7	14.5	4.32	18.9	4.84	0.69	9.0	11.8	47[d]

NOTES: [a]RESIDENTIAL MODULE
[b]NOMINAL OPERATING CELL TEMPERATURE: CELL TEMPERATURE IN OPEN-CIRCUITED MODULE EXPOSED TO 80 mW/cm² INSOLATION IN AMBIENT OF 20°C, 1 m/s WIND VELOCITY
[c]ENCAPSULATED CELL
[d]RACK-MOUNTED

Table 10. Module Mechanical Characteristics

	MANUFACTURER	MODEL NO.	AREA[b] (m^2)	LENGTH (m)[c]	WIDTH (m)[c]	MASS (kg)	SUPERSTRATE OR TOP COVER	SUBSTRATE OR BOTTOM COVER	ENCAPSULANT	ENCAPSULANT METHOD	FRAME	ELECTRICAL CONNECTIONS	PACKING FACTOR
I	SENSOR TECH.	V-13-AT	0.097	0.57	0.17	1.3	RTV-615	ALUMINUM	RTV-615	CASTING	NONE	TERMINALS	0.51
	SOLAREX	785	0.133	0.51	0.26	1.1	SYLGARD 184	NEMA-G10 BOARD	SYLGARD 184			PIGTAILS	0.61
	SOLAR POWER	E-10-229-1.5	0.229	0.61	0.37	2.6	D.C. R4-3117	NEMA-G10 BOARD	SYLGARD 184			J-BOX/CABLE	0.57
	SPECTROLAB	060513-8	0.080	0.66	0.12	1.6	GLASS	ALUMINUM	RTV-615			TERMINALS	0.49
II	SENSOR TECH.	20-10-1452-J	0.168	0.582	0.289	1.5	RTV-615	ALUMINUM	RTV-615			TERMINALS	0.64
	SOLAREX	A-0221-D	0.335	0.579	0.579	4.1	SYLGARD 184	NEMA-G10 BOARD	SYLGARD 184		ALUM.	J-BOX	0.56
	SOLAR POWER	E-10008-C	0.454	1.168	0.389	7.6	D.C. XL-2577	GFR POLYESTER BOARD	SYLGARD 184		NONE	J-BOX	0.69
	SPECTROLAB	022962-G	0.453	1.168	0.388	6.1	GLASS	MYLAR	PVB	LAMINATION	ALUM.	PLUG-IN	0.52
III	ARCO SOLAR	10699-C	0.270	1.168	0.231	3.7		TEDLAR	PVB	LAMINATION	ALUM.	TERMINALS	0.69
	MOTOROLA	P-0170-770-J	0.340	0.583	0.583	6.6		STAINLESS STEEL	D.C. 03-6527A	CASTING	ST. STEEL		0.65
	SENSOR TECH.	20-10-1646	0.166	0.582	0.286	3.7	RTV-615	ALUMINUM	RTV-615		NONE		0.65
	SOLAREX	A-0221-G	0.335	0.579	0.579	4.4	SYLGARD 184	NEMA-G10 BOARD	SYLGARD 184		ALUM.	J-BOX	0.56
	SOLAR POWER	E-10008-F	0.454	1.168	0.389	7.4	D.C. R4-3117	GFR POLYESTER BOARD	SYLGARD 184		NONE		0.69
IV	ARCO SOLAR	012110-E	0.372	1.219	0.305	5.2	GLASS	TED/ST/TED	PVB	LAMINATION	ALUM.		0.76
	ASEC	80-3062-F	0.834	1.198	0.696	13.5		TEDLAR	PVB		ALUM.	PIGTAILS	0.74
	G.E.[a]	47J254977GI-C	0.196	0.818	0.669	4.0		MEAD PAN-L-BOARD	G.E. SCS2402		NONE	FLAT-CABLE	0.76
	MOTOROLA	MSP43D40-G	0.426	1.198	0.356	5.8		TED/AL/TED	PVB		ST. STEEL	J-BOX	0.76
	PHOTOWATT	ML-1961-D	0.532	1.199	0.444	7.4		TED/AL/TED	PVB		ALUM.	PLUG-IN	0.62
	SOLAREX	580-BT-L-C	0.762	1.200	0.635	13.9		TEDLAR	EVA		ALUM.	PIGTAILS	0.85
	SOLAREX[a]	580-BT-R-C	0.749	1.193	0.628	11.2		TEDLAR			NONE	PIGTAILS	0.87
	SPIRE	058-0007-A	0.504	1.200	0.417	7.8		MYLAR-AL-COAT			ST. STEEL	PLUG-IN	0.85
V	ARCO SOLAR	004-014168-2	0.745	1.221	0.610	12.0		TED/PET/TED[e]			ALUM.	J-BOX	0.90
	G.E.[a]	47E258449G2-A	0.778	1.226	0.633	13.6		TED/PET/AL/TED[d,e]			NONE	FLAT CABLE	0.90
	MSEC[a]	Ra-180-12-D	2.154	1.791	1.203	29.5		PET/AL/TED[e]				J-BOX	0.89
	SOLAREX	C-120-10A	1.331	1.391	0.957	23.6		PET/MYLAR/TED[e]				PLUG-IN	0.88
	SPIRE[a]	058-0008-B	0.875	1.134	0.595	7.3		TEDLAR				PLUG-IN	0.76

[a]RESIDENTIAL MODULE
[b]EXPOSED AREA
[c]OVERALL DIMENSION
[d]PLUS SHINGLE MATERIAL
[e]PET=POLYESTER FILM, POLYTHYLENE TEREPHTHALATE

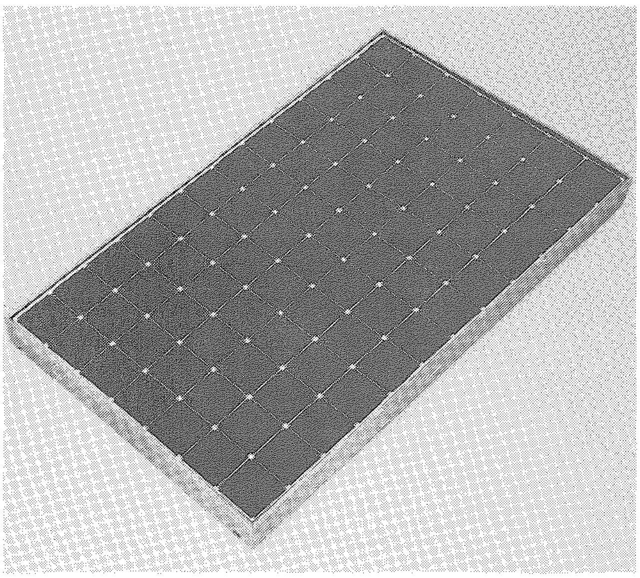


Figure 58. 15.2% Efficiency Module

D. ACCOMPLISHMENTS

Among the accomplishments of the Module Development and Testing Task are:

(1) Systematic transfer of Project technology into the PV industry was provided.

(2) Development of internationally adopted, module design configurations.

(3) Development of three module designs that have been installed in a 1 MW central power station.

(4) The DOE goal of achieving 15% module efficiency has been met.

(5) Performance of qualification tests on more than 150 different module designs, including the following:

(a) Blocks I through V.

(b) Commercial (U.S. and foreign).

(c) Residential Experiment Stations.

(d) Georgetown Project.

(e) India Project.

(f) SMUD Project.

(6) Definition of and/or quantification of numerous design deficiencies as an important management tool to focus Government and industry research and development efforts at key problem areas:

(a) Development of module inspection techniques and guidelines.

(b) Establishment of a system for reporting failures from qualification tests and field installations.

(c) Development of special failure analysis equipment and techniques.

(d) Completion of 1200 reports of failures, involving 435 major failure analyses.

(7) Elevation of the credibility of the PV industry by providing an internationally recognized assessment of PV-module electrical performance and reliability.

(8) Development of a world-class solar simulator with both direct normal and global AM 1.5 irradiance spectra.

(9) Participation in international round-robins of reference-cell measurements to resolve measurements discrepancies and develop standards.

(10) Provision of primary calibrated reference cells to most U.S. manufacturers.

(11) Development of a simple, accurate method for secondary calibration of reference cells leading to calibration of cells for many U.S. and foreign PV manufacturers.

SECTION VI

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APPENDIX A
Bibliography

This Appendix provides a comprehensive listing of all published work resulting from the Engineering Sciences and Reliability activities of the FSA Project as described in this report. Guidelines for acquiring the references are provided in Appendix B.

Appendix Organization

The Appendix is organized by research subject to aid the reader in finding all work related to a specific topic of interest. Therefore, reports with important contributions to more than one topic are generally listed under each appropriate topic. The organization of topics more or less parallels that of the report itself except that module-level and array-level technologies have been broken out separately. As noted in the Contents, the published works are subdivided into five major categories:

Module Requirements and Electrical Performance Rating

Overall Array Design Requirements, Concepts and Engineering Methods

Module Engineering and Reliability Technology

Module Development and Test Experience

Summaries and Proceedings

The first four categories are divided into a total of 33 topical subjects that span the developed technologies. Within each subject, the reports are listed chronologically. The fifth category provides a complete listing of Project-wide documents, progress reports, and workshop proceedings which span many areas of interest. Specifically noteworthy contributions within these summaries are often referenced separately within the 33 technology categories, especially if no other reference covers the reported work. Because of the late addition of the FSA Encapsulation Task to this area in 1984 and the existence of a separate final report (Volume VII) covering the encapsulation work, encapsulation references are limited to key summary documents and important published work in topical areas historically covered by the Engineering Sciences and Reliability research.

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APPENDIX B

Acquisition of References

Most of the references used in this report fall into one of four generic types: (1) JPL published reports, (2) reports prepared for JPL by an outside contractor, (3) articles in the proceedings of professional meetings, and (4) articles in professional journals.

JPL Published Reports

These reports nearly always contain an FSA project document number of the form 5101-xxx, and may also contain a JPL Publication number (such as JPL Publication 83-52) and/or a Federal Government sponsor number in the form of DOE/JPL-1012-xx. Only those reports containing a JPL Publication number can be easily obtained from JPL. These can be obtained from:

Jet Propulsion Laboratory
Documentation and Materiel Division
4800 Oak Grove Dr.
Pasadena, CA 91109

JPL reports containing the Federal Government sponsor number DOE/JPL-1012-xx can be obtained from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161

or

U.S. Department of Energy
Technical Information Center
Publication Request Section
P.O. Box 62
Oak Ridge, TN 37831

JPL reports without a JPL publication number or Federal Government sponsor number are internal JPL reports. They are sometimes available from the Documentation and Materiel Division, which determines their releasability with the author's organization, assuming copies are still in print.

JPL Contractor Reports

These reports are available from the National Technical Information Service (NTIS) at the Springfield, Virginia, address given above, using the Federal Government sponsor number (DOE/JPL 9xxxxx-xx) associated with the reference. They are generally not available from either JPL or the contractor who prepared the report.

Technical Conference Proceedings

Several technical conferences have been widely used for publishing papers due to the relevance of their scope, their rapid turn-around, and their wide availability. Key conference proceedings and their associated publishers include:

(1) IEEE Photovoltaic Specialists Conference
Institute of Electrical and Electronic Engineers, Inc.
345 E. 47th Street
New York, NY 10017

(2) American Solar Energy Society (ASES)
Formerly American Section of the International Solar Energy Society (AS/ISES)
Publications Director
2030 17th Street
Boulder, CO 80302

(3) Institute of Environmental Sciences (IES)
940 E. Northwest Highway
Mt. Prospect, IL 60056

(4) Commission of European Communities (EC)
Photovoltaic Solar Energy Conference
D. Reidel Publishing Company
P.O. Box 17, 3300 AA Dordrecht, Holland
(or in U.S.)
Kluwer Boston, Inc.
190 Old Denby St.
Hingham, MA 02043

(5) Intersociety Energy Conversion Engineering Conference
Published by American Chemical Society
1155 Sixteenth St., NW
Washington, D.C. 20036

(6) American Institute of Aeronautics and Astronautics (AIAA)
AIAA Library
750 3rd Ave.
New York, NY 10017

(7) American Society of Mechanical Engineers (ASME)
United Engineering Center
345 E. 47th St.
New York, NY 10017

Professional Journals

These are widely available from technical libraries.

APPENDIX C

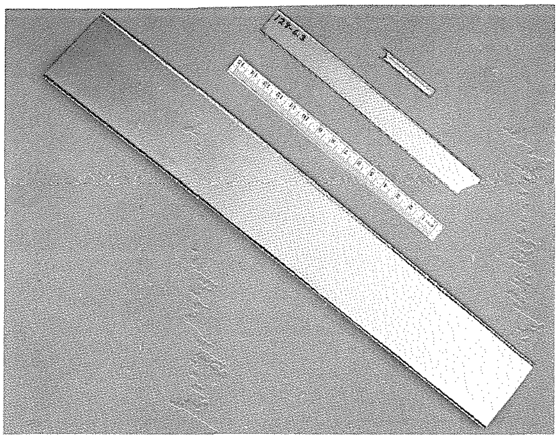
Glossary

AC	alternating current
AR	antireflective
ASTM	American Society for Testing and Materials
CRT	cathode ray tube
Cz	Czochralski
DC	direct current
DOE	U.S. Department of Energy
EVA	ethylene vinyl acetate
FSA	Flat-Plate Solar Array (Project)
FZ	float zone
GE	General Electric
IEEE	Institute of Electrical and Electronics Engineers, Inc.
I-V	current-voltage
JPL	Jet Propulsion Laboratory
LAPSS	Large-Area Pulsed Solar Simulator
LSSA	Low-Cost Silicon Solar Array (Project)
MIT	Massachusetts Institute of Technology
MOV	metal-oxide varistor
MPFA	Module Performance and Failure Analysis
NASA	National Aeronautics and Space Administration
NEC	National Electrical Code
NOCT	Nominal Operating Cell Temperature
PRDA	Program Research and Development Announcement
PV	photovoltaic (s)
PVB	polyvinyl butyral
PV-T	photovoltaic/thermal
QA	quality assurance
SERI	Solar Energy Research Institute
SMUD	Sacramento Municipal Utility District
SOLMET	Solar Radiation-Surface Meteorological Observations
UL	Underwriters Laboratories
UV	ultraviolet

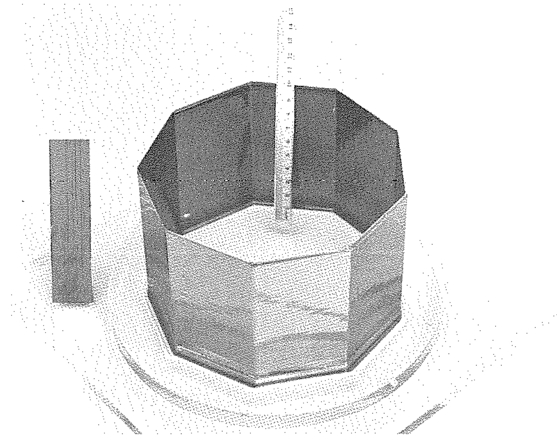
Prepared by the Jet Propulsion Laboratory, California Institute of Technology, for the U.S. Department of Energy through an agreement with the National Aeronautics and Space Administration.

The JPL Flat-Plate Solar Array Project is sponsored by the U.S. Department of Energy and is part of the National Photovoltaics Program to initiate a major effort toward the development of cost-competitive solar arrays.

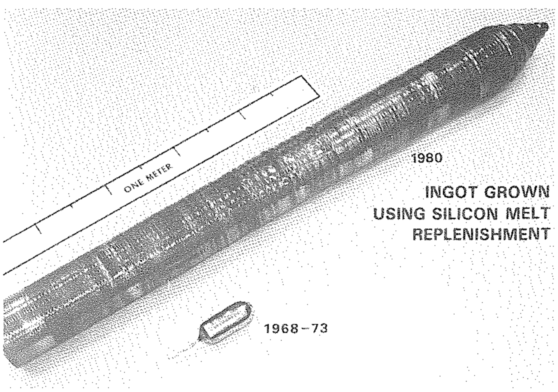
More Technology Advancements



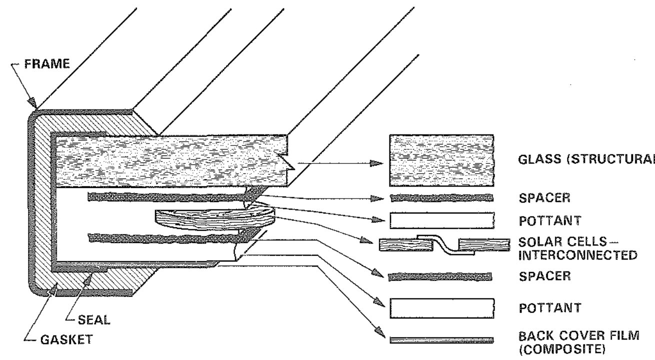
Dendritic web silicon ribbons are grown to solar-cell thickness. Progress is shown by experimental ribbons grown in 1976 and 1978 and a ribbon grown in a Westinghouse Electric Corporation pilot plant.



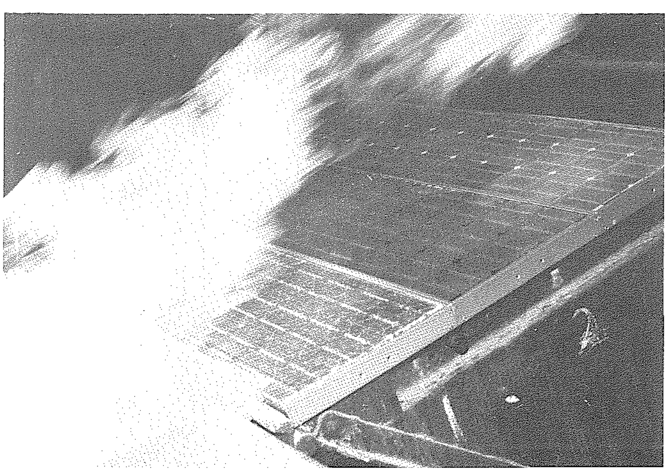
The edge-defined film-fed growth silicon ribbons are grown to solar-cell thickness. A DOE/FSA-sponsored research ribbon grown in 1976 is shown next to a nine-sided ribbon grown in a Mobil Solar Energy Corporation funded configuration.



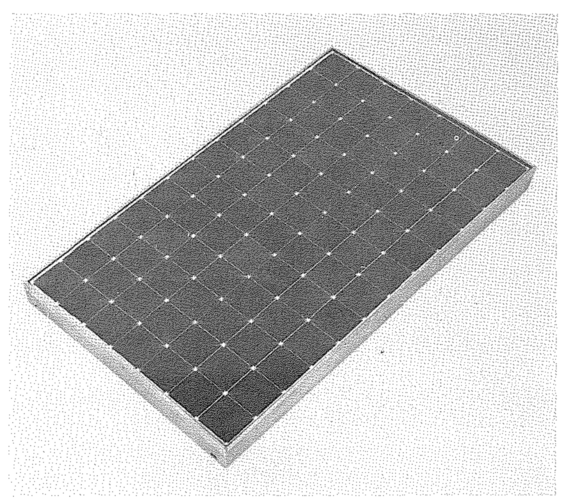
Czochralski silicon crystals as grown are sawed into thin circular wafers. (Support for this effort was completed in 1981.)



Typical superstrate module design is shown with the electrically interconnected solar cells embedded in a laminate that is structurally supported by glass. Materials and processes suitable for mass production have been developed using this laminated design.



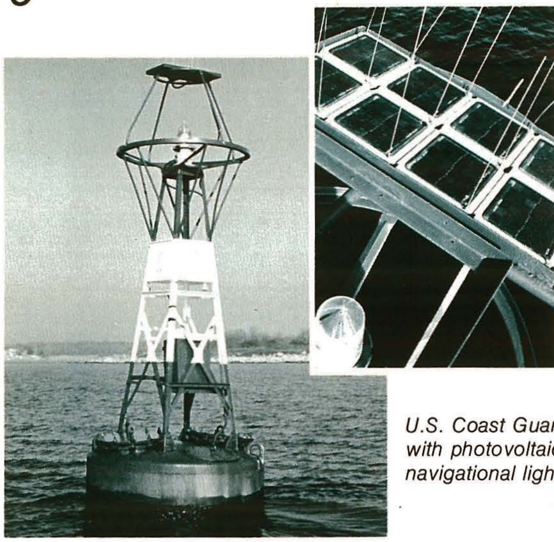
Prototype modules have passed UL 790 Class A burning brand tests which are more severe than this spread of flame test.



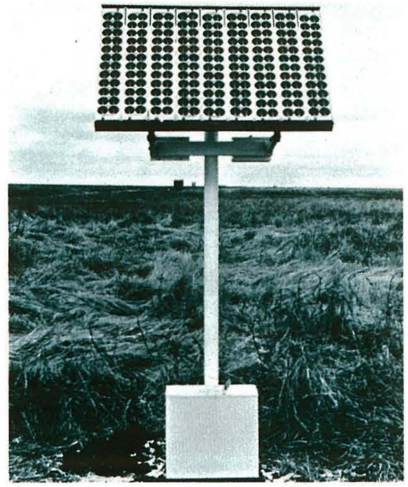
A 15.2% efficiency prototype module (21 x 36 in.) was made by Spire Corp. using float-zone silicon wafers. Recently, similarly efficient modules were fabricated from Czochralski silicon wafers.

Photovoltaic Applications

1975

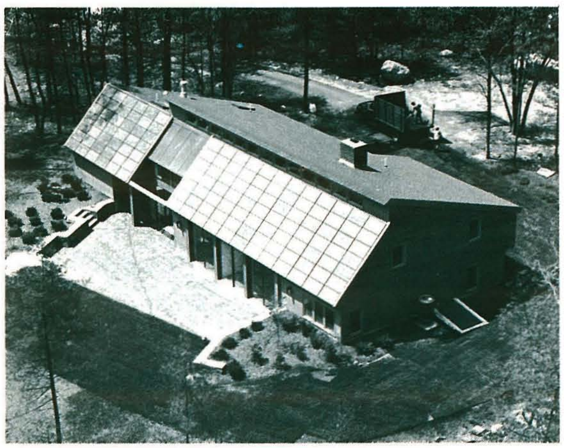


U.S. Coast Guard buoy with photovoltaic-powered navigational light.

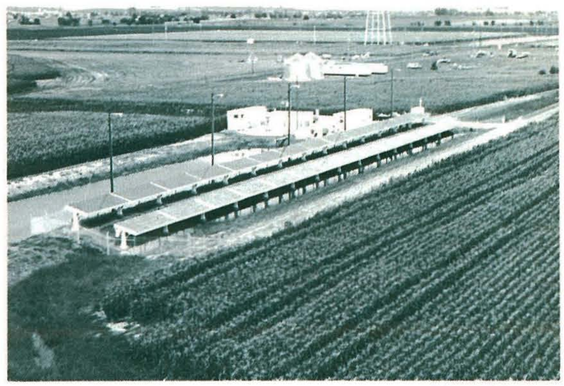


Photovoltaic-powered corrosion protection of underground pipes and wells.

Later...



House in Carlisle, Massachusetts, with a 7.3-kW photovoltaic rooftop array. Excess photovoltaic-generated power is sold to the utility. Power is automatically supplied by the utility as needed.



A 28-kW array of solar cells for crop irrigation during summer, and crop drying during winter (a DOE/University of Nebraska cooperative project).

1985

1.2 MW of photovoltaic peaking-power generation capacity for the Sacramento Municipal Utility District. (The 8 x 16 ft panels are mounted on a north-south axis for tracking the sun.)